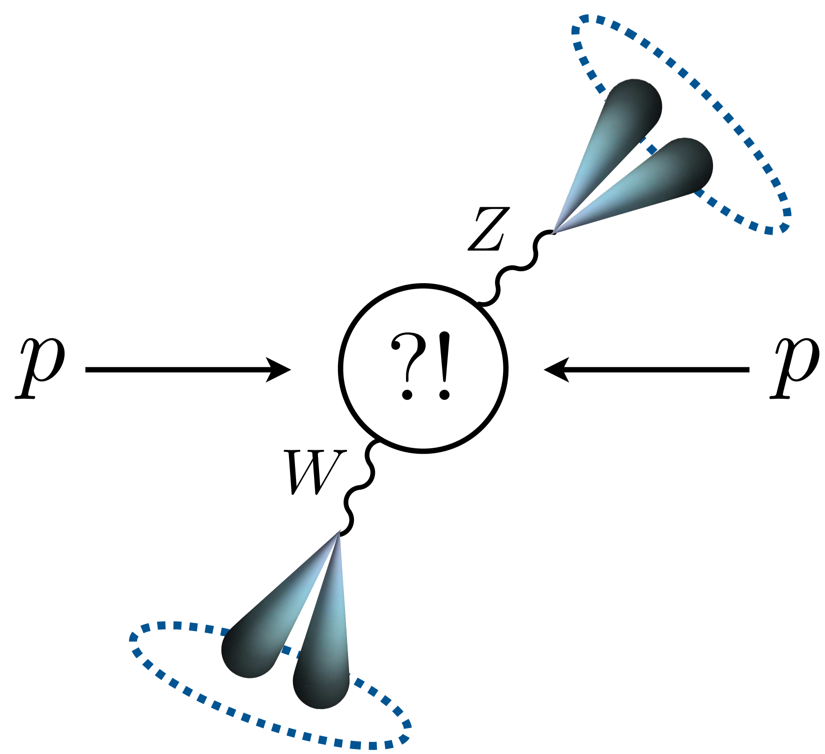
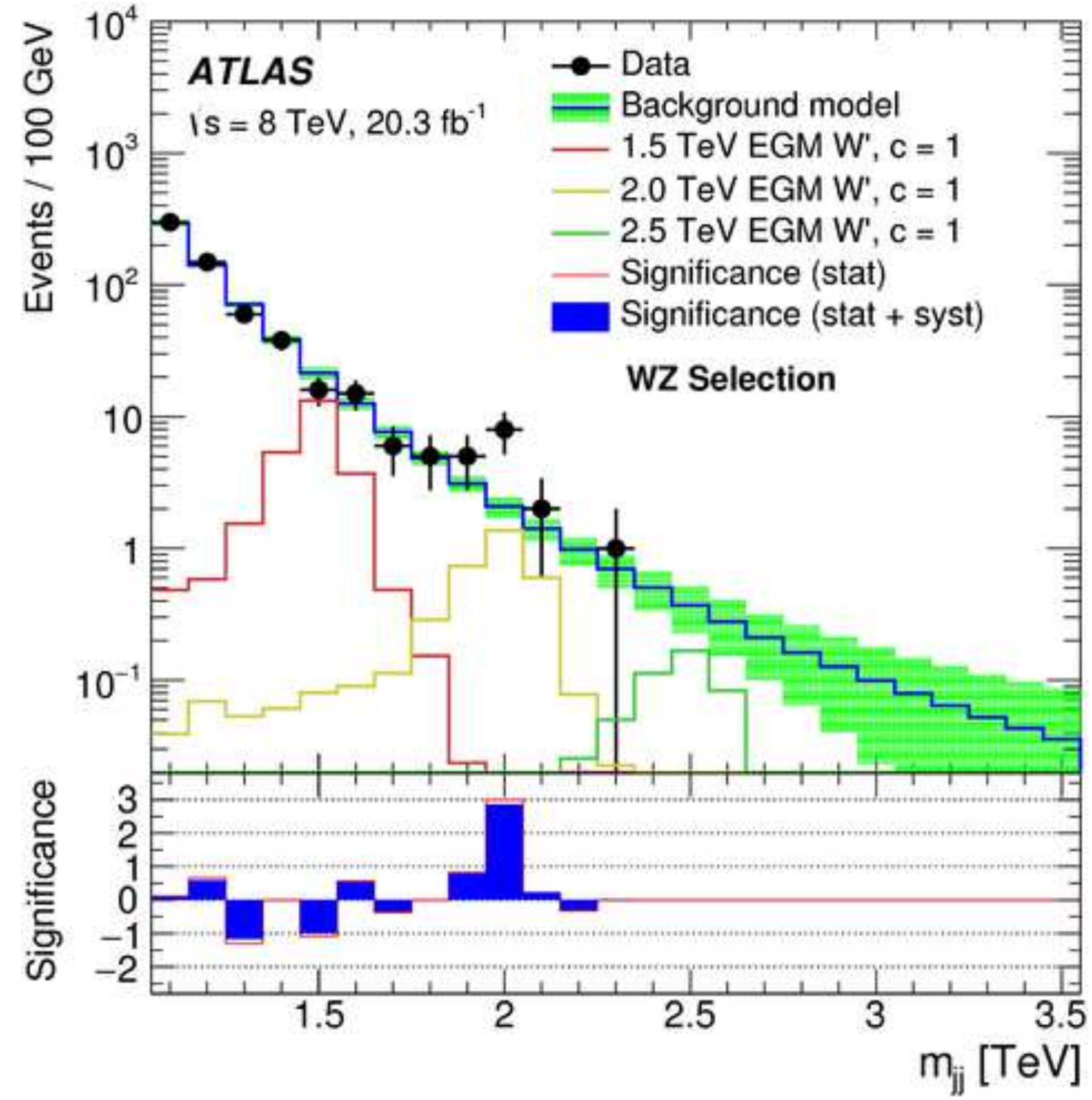
Theoretical Advances in Jet Substructure

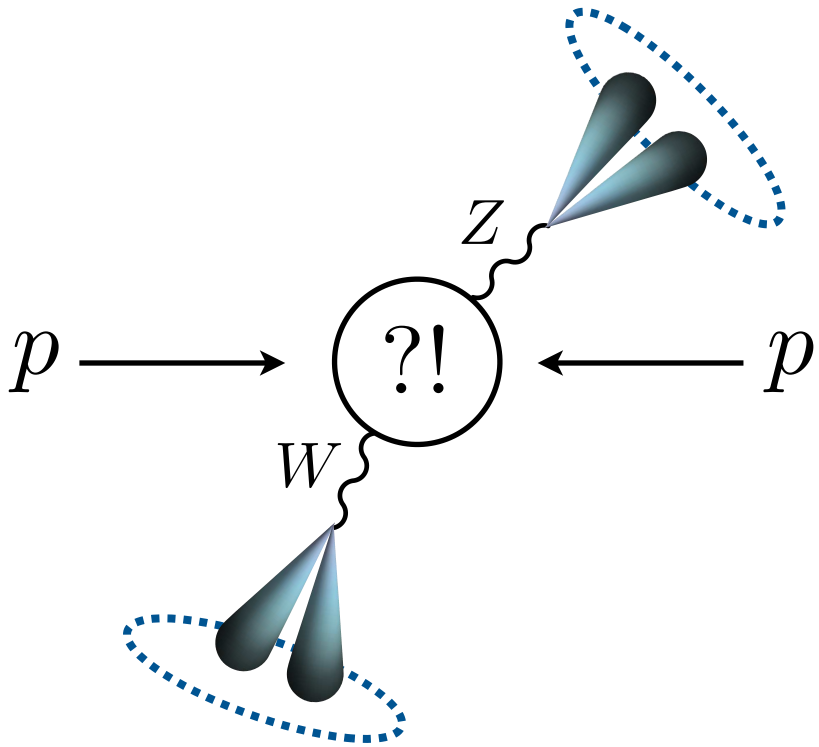
Jesse Thaler

“Stress-testing the Standard Model at the LHC”, KITP — May 23, 2016

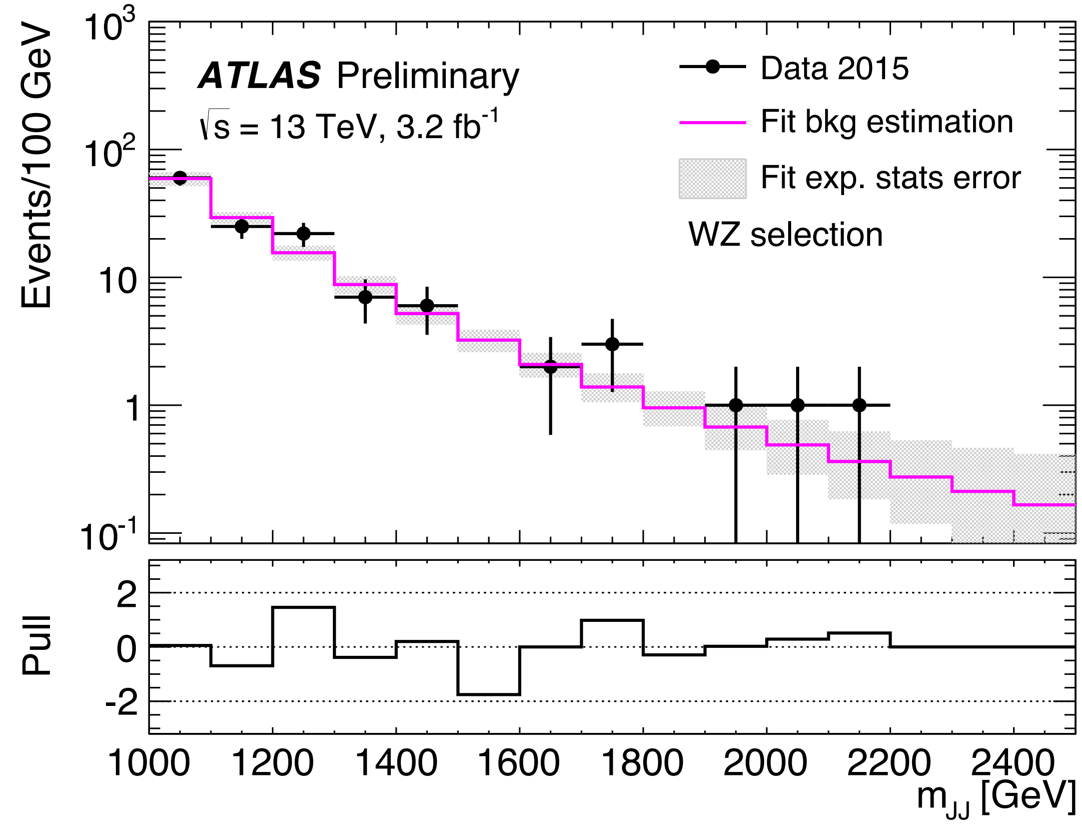


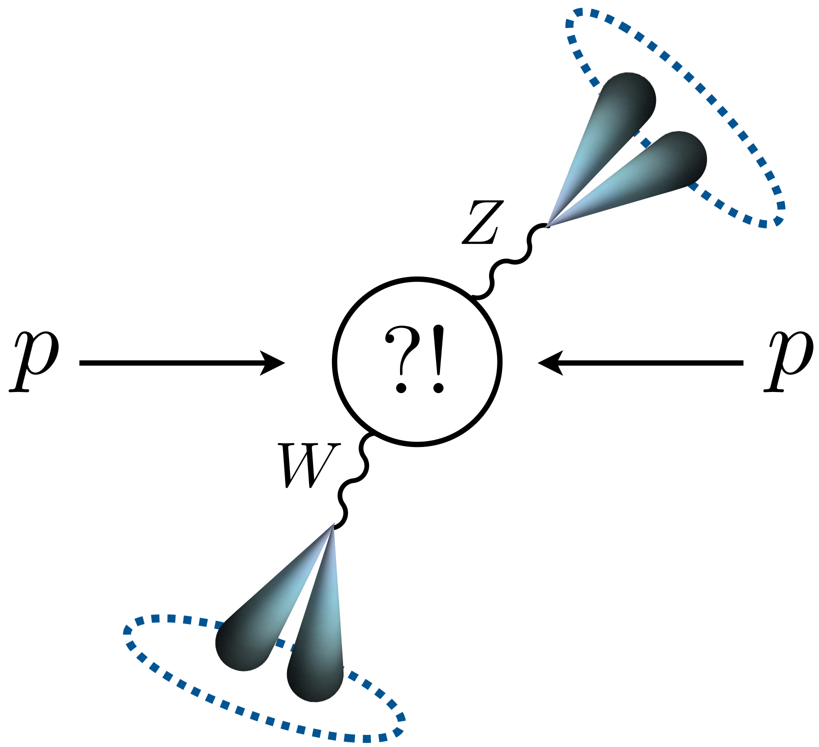
[ATLAS, 1506.00962]

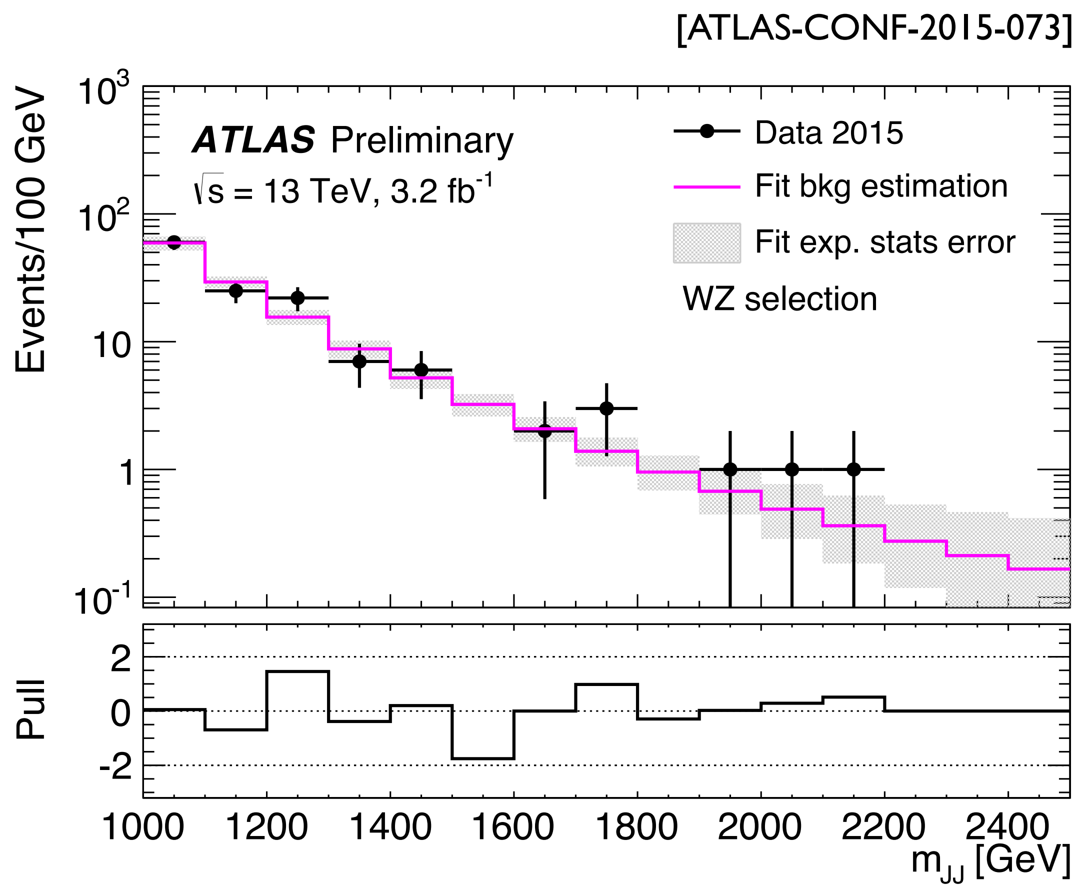


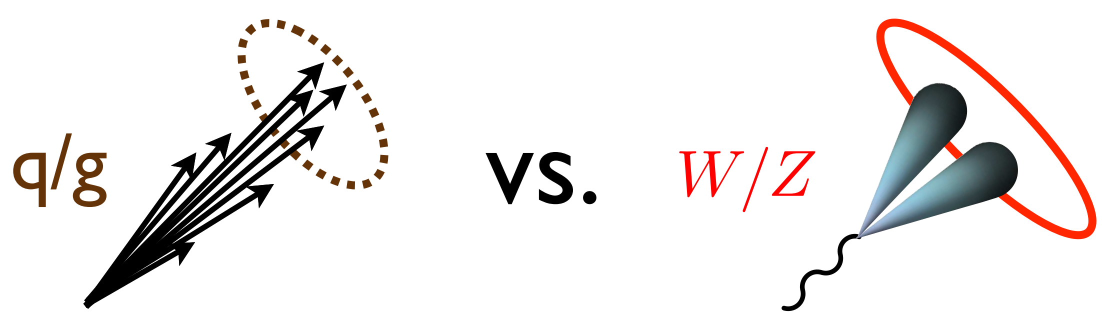


[ATLAS-CONF-2015-073]



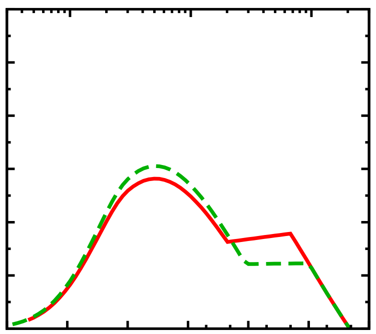




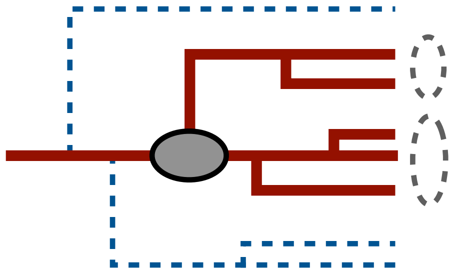


Simple discriminant requires new calculational techniques

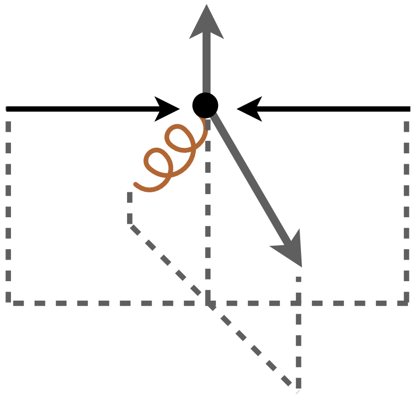
Outline



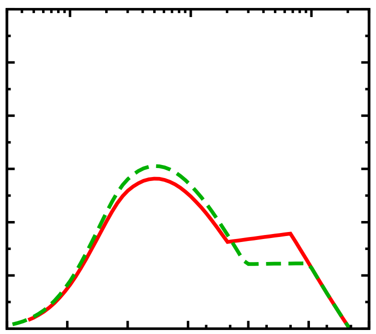
Substructure from First Principles



Probing the Core of QCD



Back to the Future



Substructure from First Principles

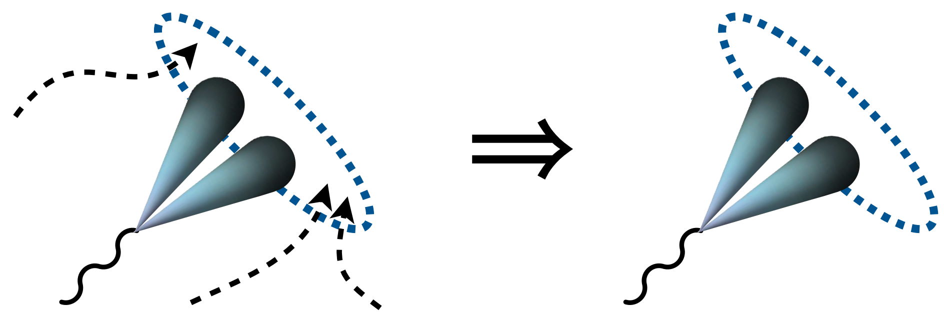
Probing the Core of QCD

Back to the Future

Key Substructure Techniques

Jet Cleaning:

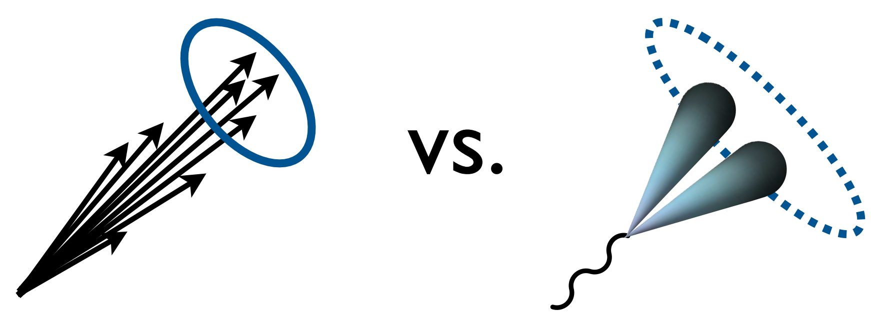
e.g. ISR/UE/pileup



[Mass Drop/Filtering, Trimming, Pruning, Soft Drop, Jet Reclustering…;
for pileup: Area Subtraction, Jet Cleansing, SoftKiller, PUPPI, Constituent Subtraction…]

Discrimination:

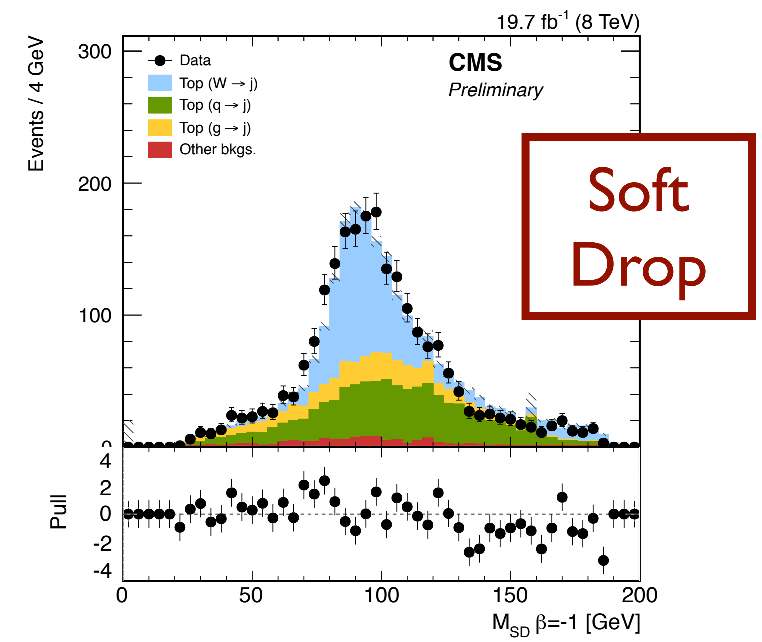
e.g. 1-prong vs. N-prong



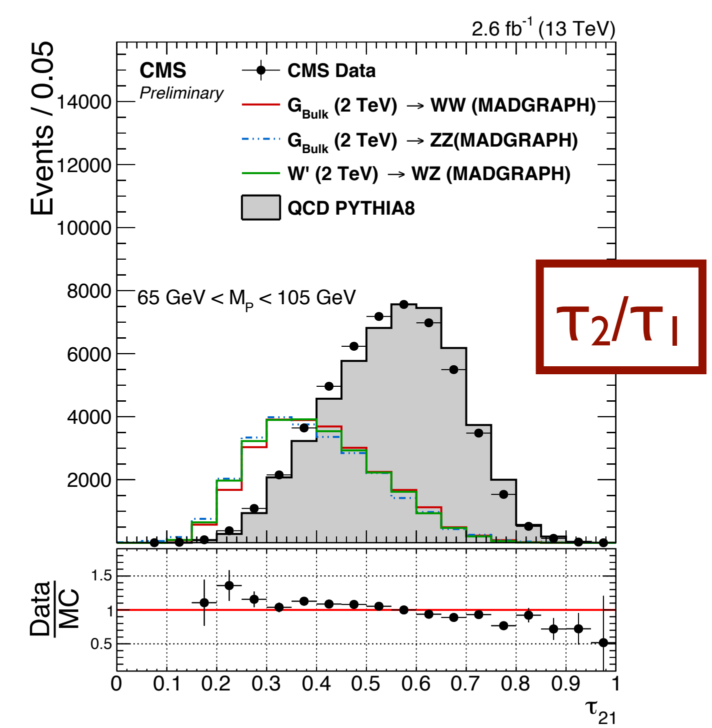
[p_T Balance, Y-splitter, Angularities, Planar Flow, N-subjettiness, Angular Structure Functions, Jet Charge, Jet Pull, Energy Correlation Functions, Dipolarity, p_T^D, Zernike Coefficients, LHA, Fox-Wolfram Moments, JHU/CMSTopTagger, HEPTopTagger, Template Method, Shower Deconstruction, Subjet Counting, Wavelets, Q-Jets, Telescoping Jets…]

W/Z-Tagging @ CMS

[JME-14-002, CMS-PAS-EXO-15-002]



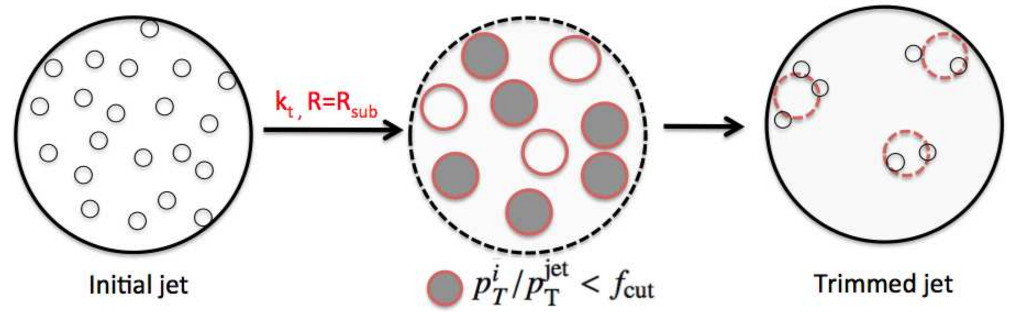
[using Larkoski, Marzani, Soyez, JDT, 1402.2657]



[using JDT, Van Tilburg, 1011.2268, 1108.2701]

First-Principles Calculations?

e.g. Jet Trimming

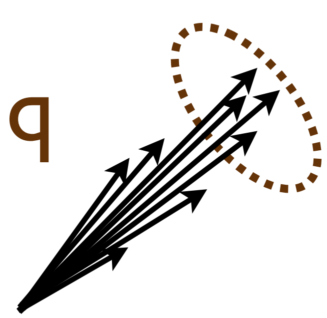


extensively used by ATLAS

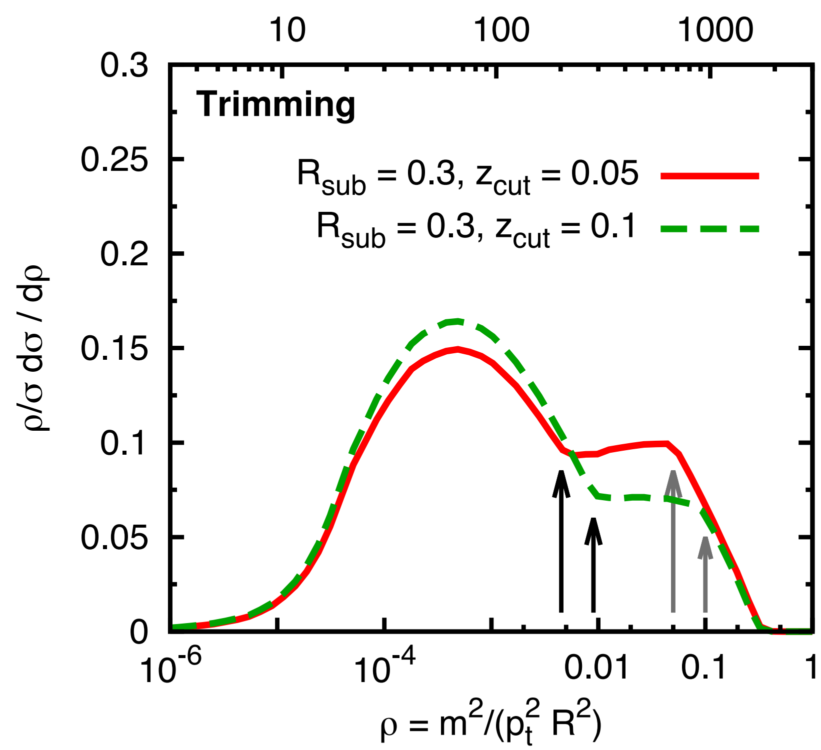
[Krohn, JDT, Wang, 0912.1342; diagram from ATLAS, 1306.4945]

Trimmed Jet Mass:

3 TeV quark jets



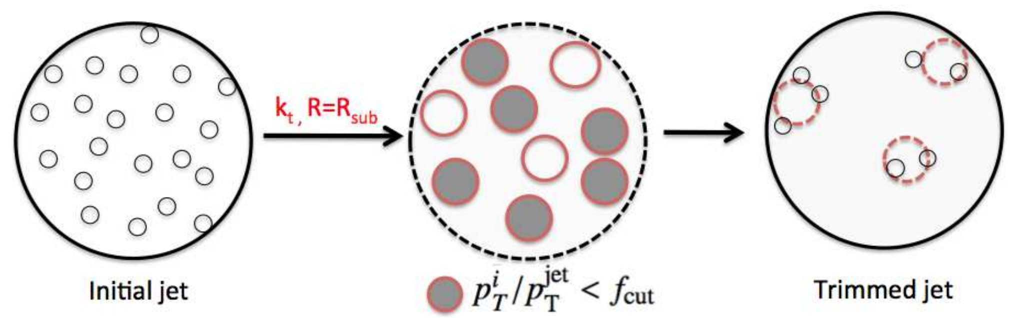
Pythia 6 Simulation



[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

First-Principles Calculations?

e.g. Jet Trimming



extensively used by ATLAS

[Krohn, JDT, Wang, 0912.1342; diagram from ATLAS, 1306.4945]

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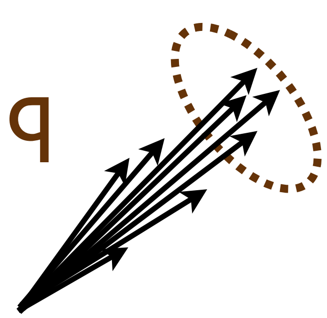
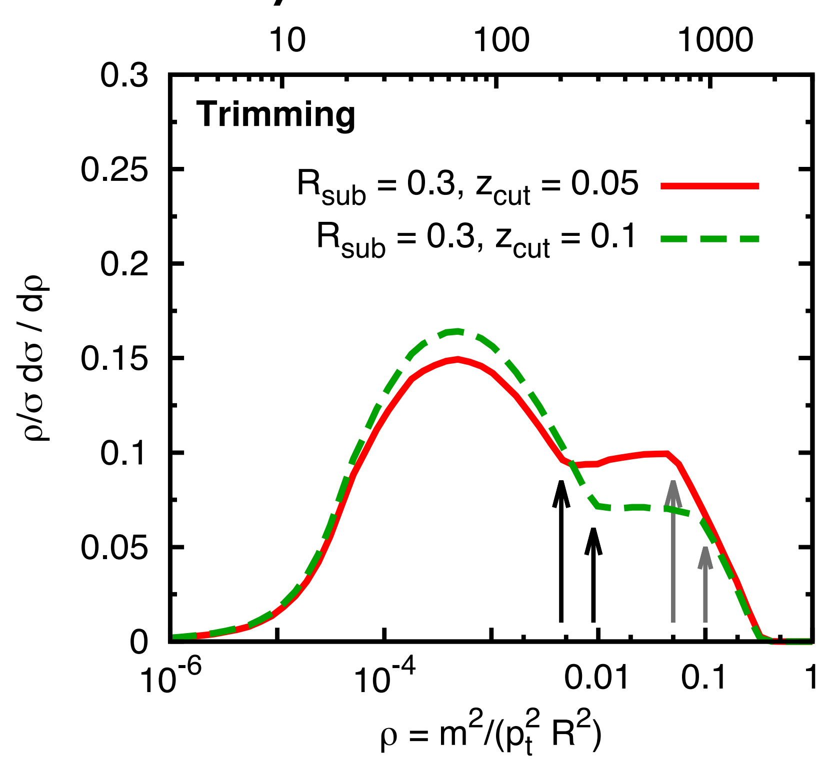
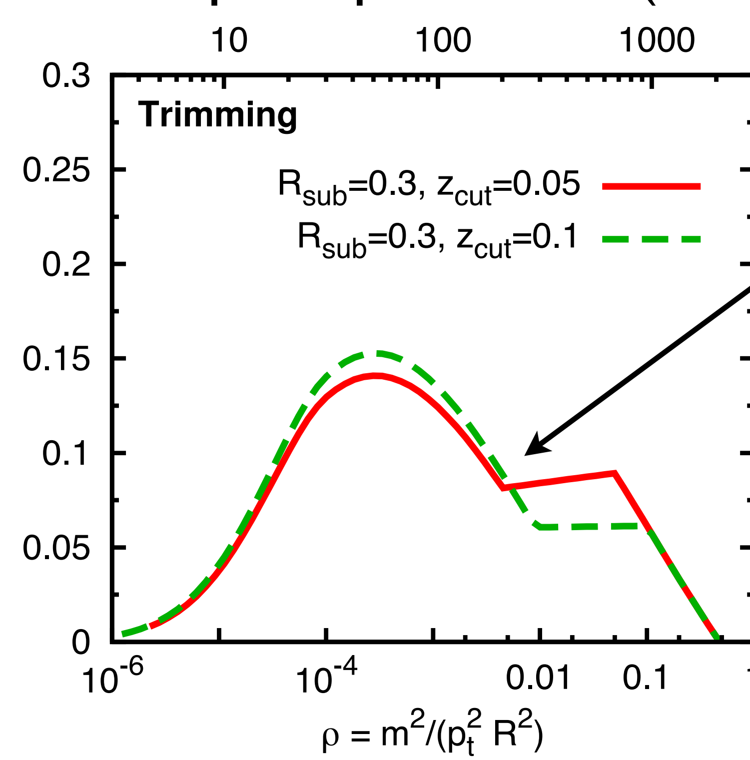


Pythia 6 Simulation



First-principles QCD (MLL)



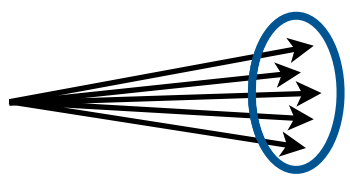
Analytically understand Sudakov peak, kinks, and plateau

[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Recent Analytic Progress

Combination of fixed-order, direct resummation, SCET, RG evolution, and new techniques (e.g. Sudakov safety, multi-differential projections)

1-prong:



Jet mass: Dasgupta, Khelifa-Kerfa, Marzani, Spannowsky, 1207.1640; Chien, Kelley, Schwartz, Zhu, 1208.0010; Jouttenus, Stewart, Tackmann, Waalewijn, 1302.0846

Jet shapes: Ellis, Vermilion, Walsh, Hornig, Lee, 1001.0014; Banfi, Dasgupta, Khelifa-Kerfa, Marzani, 1004.3483; Li, Li, Yuan, 1107.4535; Larkoski, Neill, JDT, 1401.2158; Hornig, Makris, Mehen, 1601.01319

Angular scaling: Jankowiak, Larkoski, 1201.2688; Larkoski, 1207.1437

Quarks vs. gluons: Larkoski, Salam, JDT, 1305.0007; Larkoski, JDT, Waalewijn, 1408.3122; Bhattacherjee, Mukhopadhyay, Nojiri, Sakaki, Webber, 1501.04794

QCD grooming: Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Dasgupta, Fregoso, Marzani, Powling, 1307.0013; Larkoski, Marzani, Soyez, JDT, 1402.2657; Frye, Larkoski, Schwartz, Yan, 1603.06375, 1603.09338

Double differential: Larkoski, JDT, 1307.1699; Larkoski, Moult, Neill, 1401.4458; Procura, Waalewijn, Zeune, 1410.6483

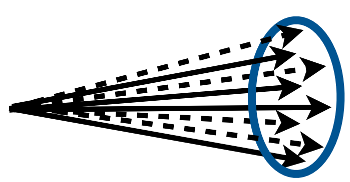
In heavy ions: Chien, Vitev, 1405.4293; Chien, 1411.0741

p_T balance: Larkoski, Marzani, JDT, 1502.01719

Small R jets: Dasgupta, Dreyer, Salam, Soyez, 1411.5182, 1602.01110

See Andrew's Talk

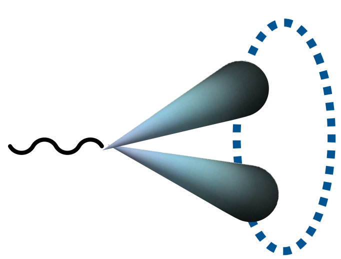
Non-pert.:



Jet charge: Krohn, Schwartz, Lin, Waalewijn, 1209.2421; Waalewijn, 1209.3019

Track-only shapes: Chang, Procura, JDT, Waalewijn, 1303.6637, 1306.6630

2-prong:

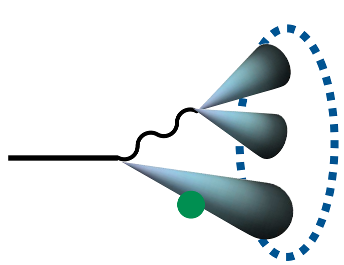


Signal grooming: Rubin, 1002.4557; Dasgupta, Powling, Siodmok, 1503.01088

2-prong jet shapes: Feige, Schwartz, Stewart, JDT, 1204.3898; Isaacson, Li, Li, Yuan, 1505.06368

Separation power: Larkoski, Moult, Neill, 1409.6298, 1507.03018; Dasgupta, Schunk, Soyez, 1512.00516

3-prong:



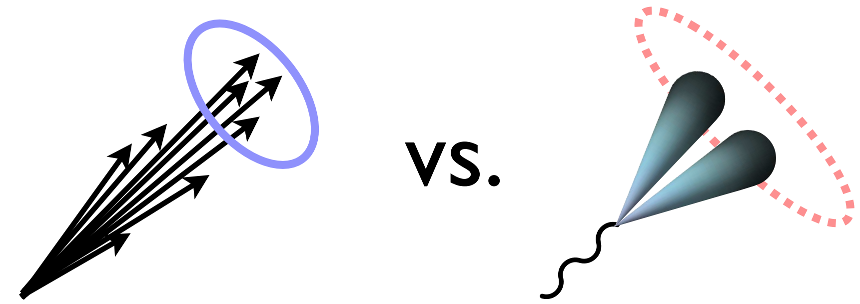
Planar flow: Field, Gur-Ari, Kosower, Mannelli, Perez, 1212.2106

Fractional jets: Bertolini, JDT, Walsh, 1501.01965

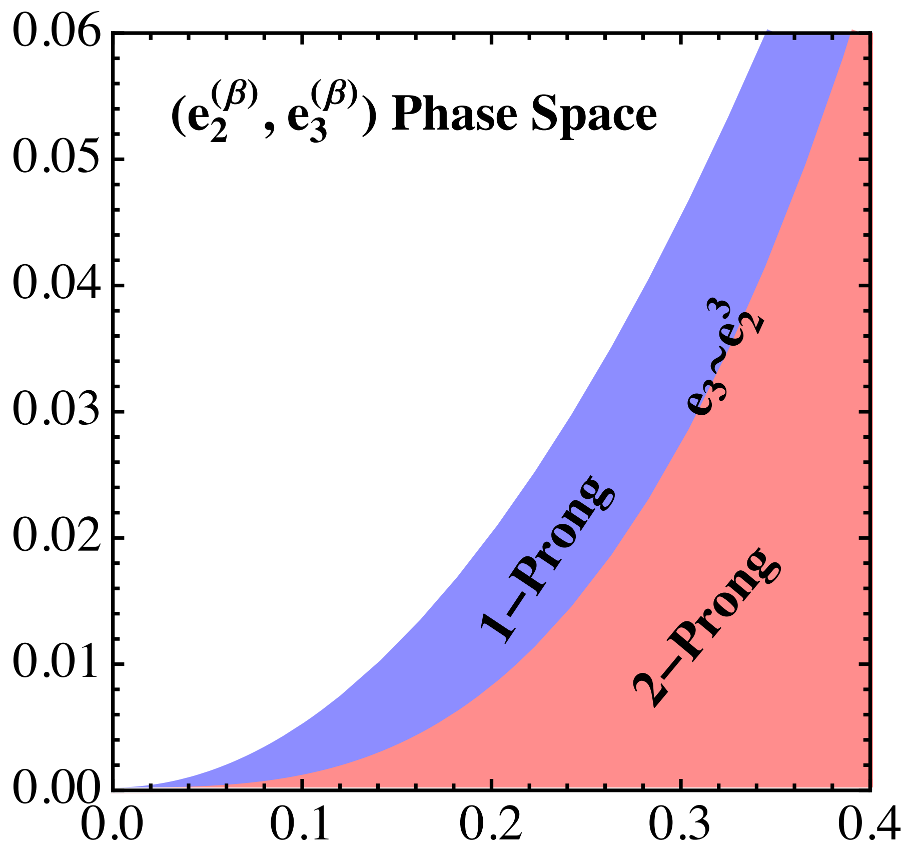
Power counting: Larkoski, Moult, Neill, 1411.0665

The Power of Power Counting

Energy correlation functions for W/Z tagging



$$e_3 = \sum_{i<j<k} z_i z_j z_k R_{ij} R_{jk} R_{ki}$$

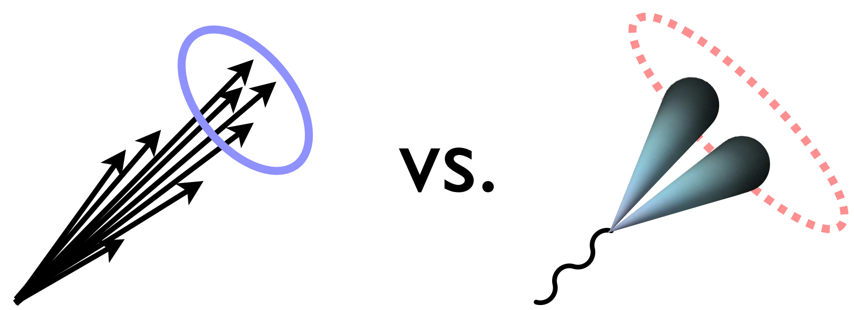


$$e_2 = \sum_{i<j} z_i z_j R_{ij}$$

[Larkoski, Moult, Neill, 1409.6298,1507.03018; using Larkoski, Salam, JDT, 1305.0007; see also Banfi, Salam, Zanderighi, hep-ph/0407286; Jankowiak, Larkoski, 1104.1646]

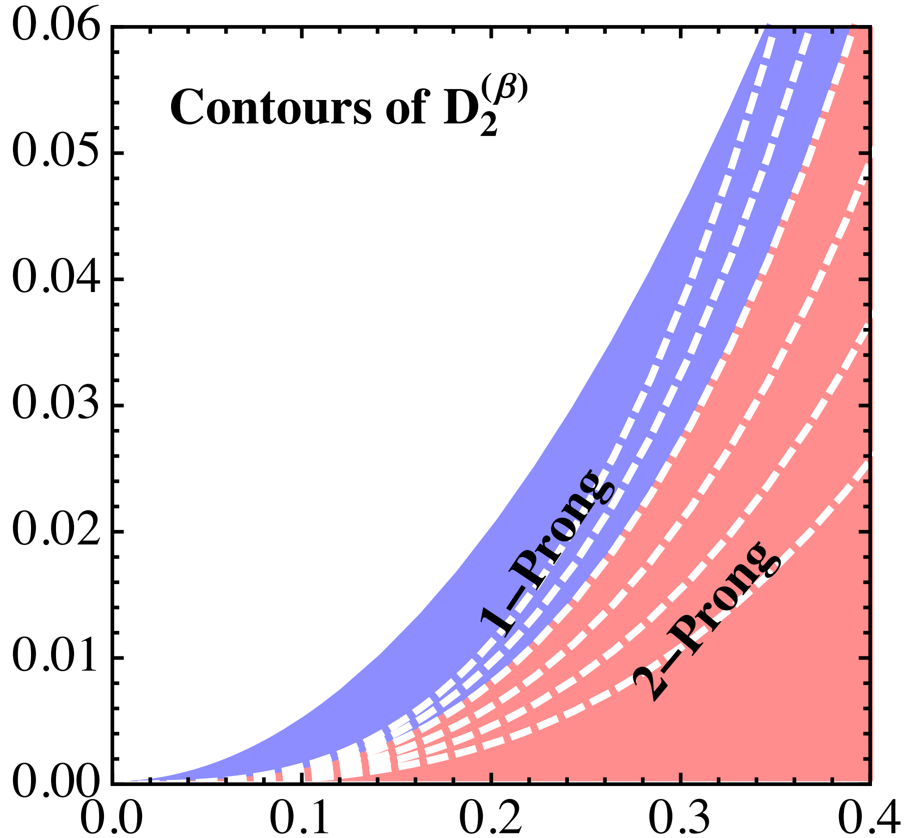
The Power of Power Counting

Energy correlation functions for W/Z tagging

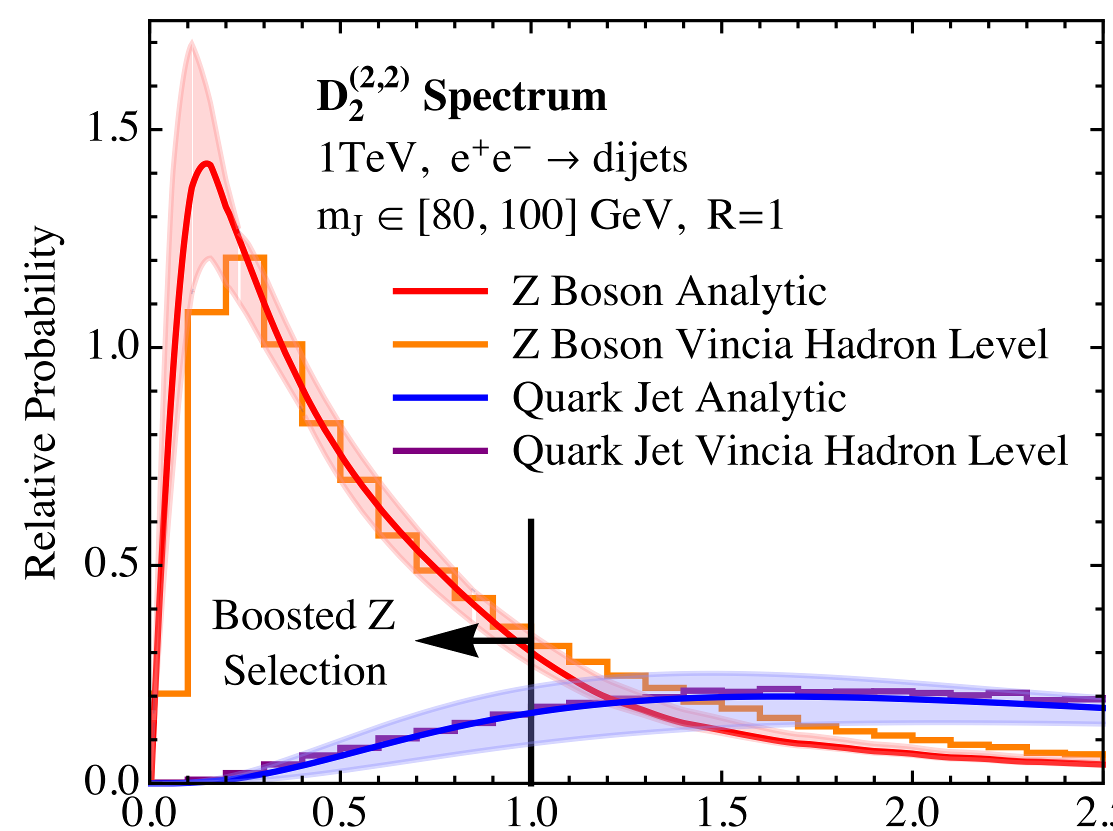


Basis for ATLAS
“R2 D_2” tagger

$$e_3 = \sum_{i<j<k} z_i z_j z_k R_{ij} R_{jk} R_{ki}$$



$$e_2 = \sum_{i<j} z_i z_j R_{ij}$$



$$D_2 = \frac{e_3}{(e_2)^3} \longleftarrow \text{key!}$$

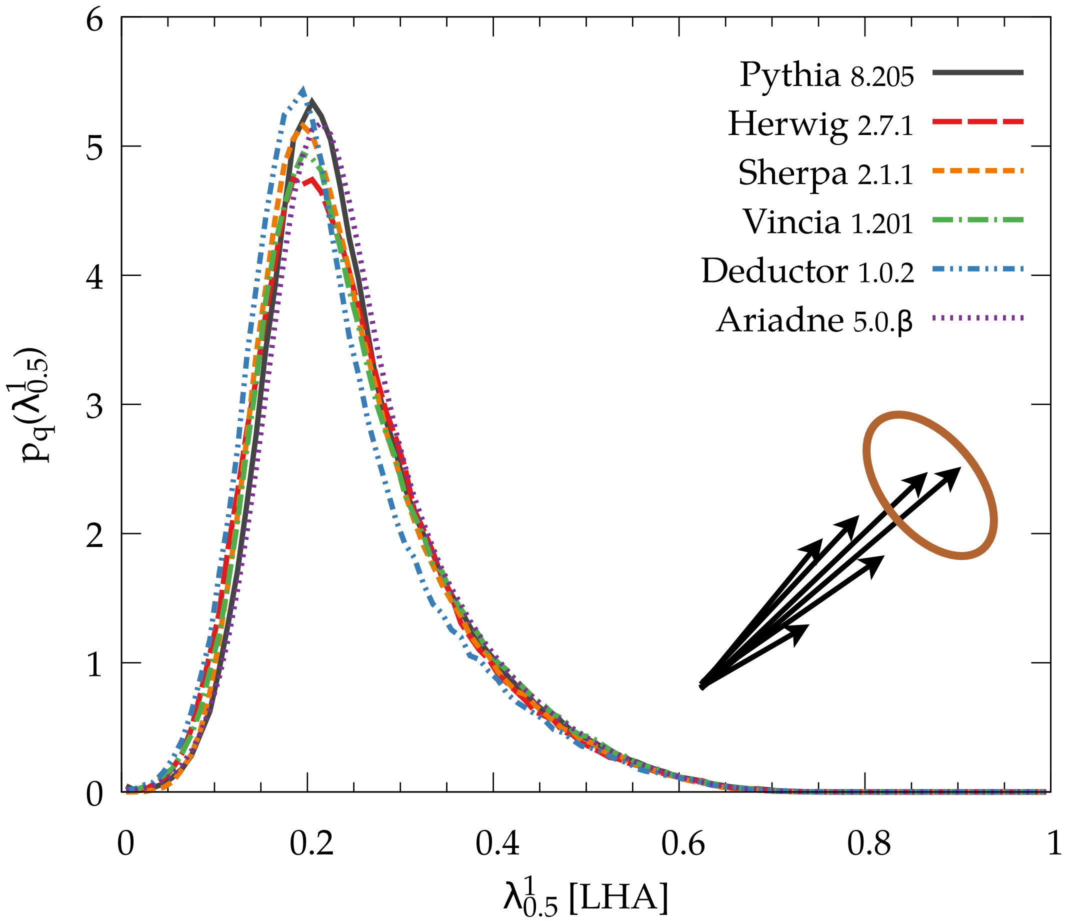
[Larkoski, Moult, Neill, 1409.6298,1507.03018; using Larkoski, Salam, JDT, 1305.0007; see also Banfi, Salam, Zanderighi, hep-ph/0407286; Jankowiak, Larkoski, 1104.1646]

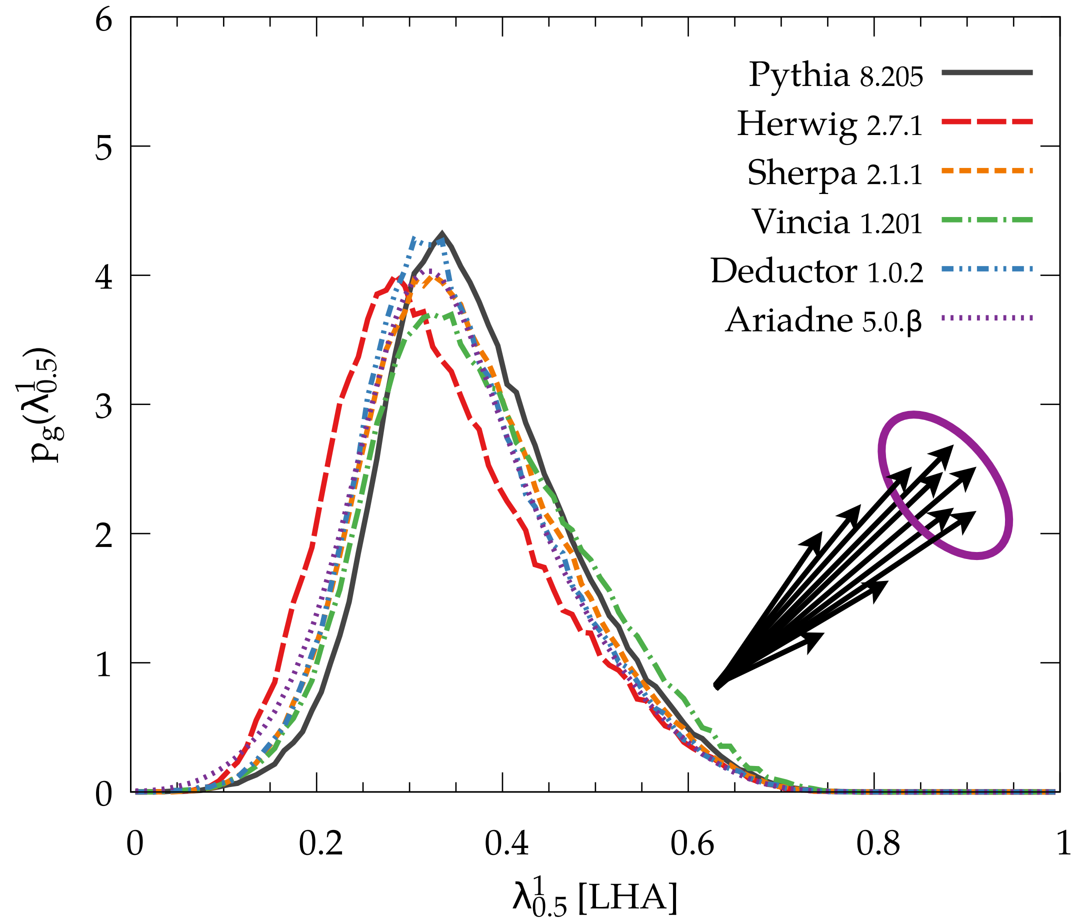
Quarks vs. Gluons?

Tagging with Les Houches Angularity

$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

$e^+e^- \to$ quarks ($C_F = 4/3$) *vs.* $e^+e^- \to$ gluons ($C_A = 3$)



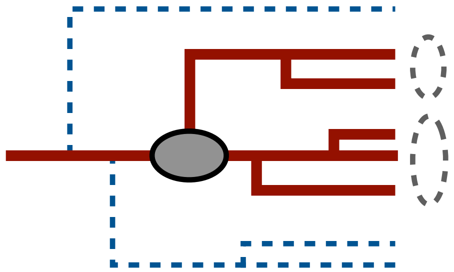


Factor of 2 differences in tagging performance

Need for precision calculations and revisiting final state parton shower

[Soyez, JDT, Freytsis, Gras, Kar, Lönnblad, Plätzer, Siodmok, Skands, Soper, in 1605.04692]

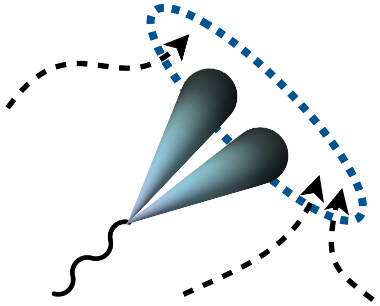
Substructure from First Principles



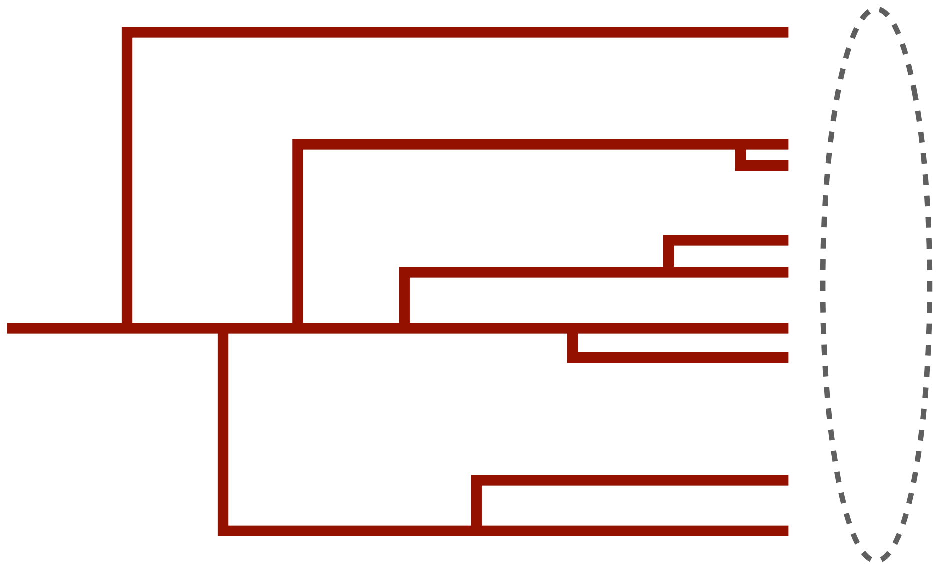
Probing the Core of QCD

Back to the Future

W/Z Tagging with BDRS

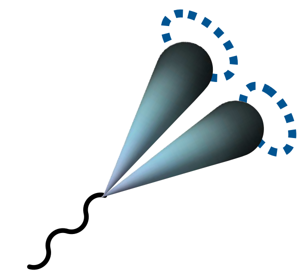


Angular-ordered clustering tree:

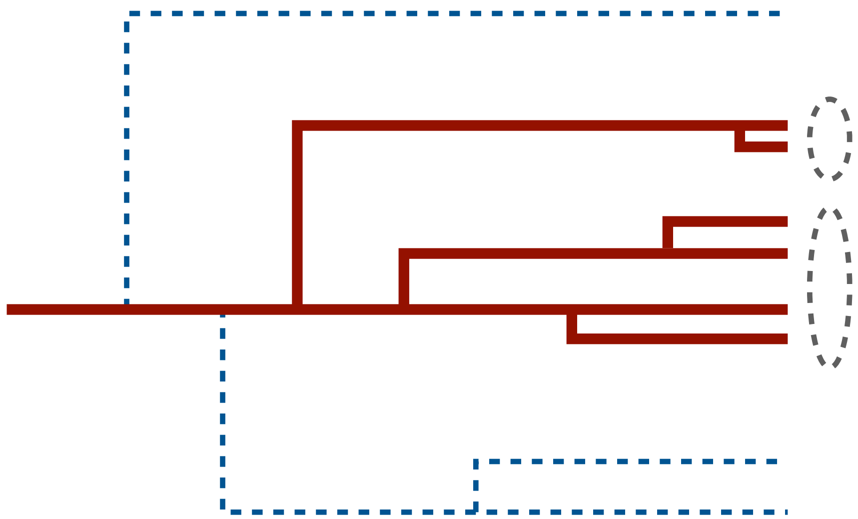


[Butterworth, Davison, Rubin, Salam, 0802.2470; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

W/Z Tagging with BDRS

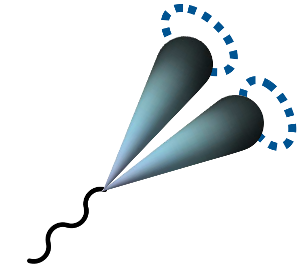


Groomed angular-ordered clustering tree:

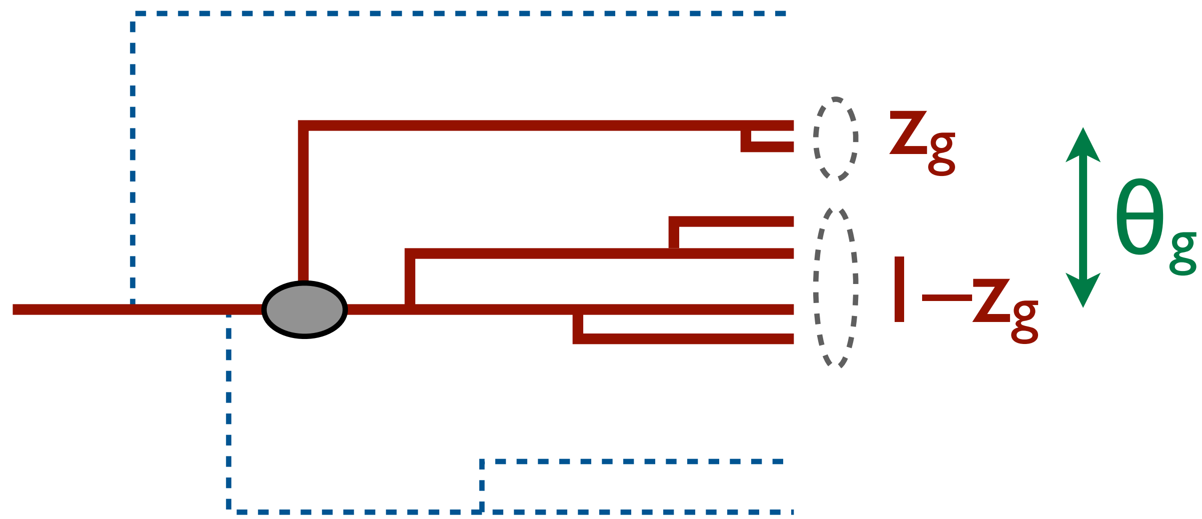


[Butterworth, Davison, Rubin, Salam, 0802.2470; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

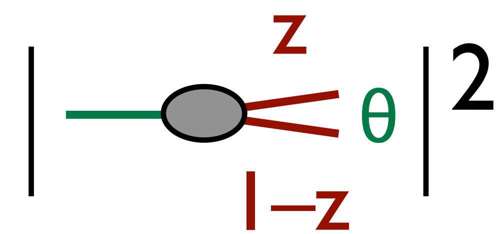
W/Z Tagging with BDRS



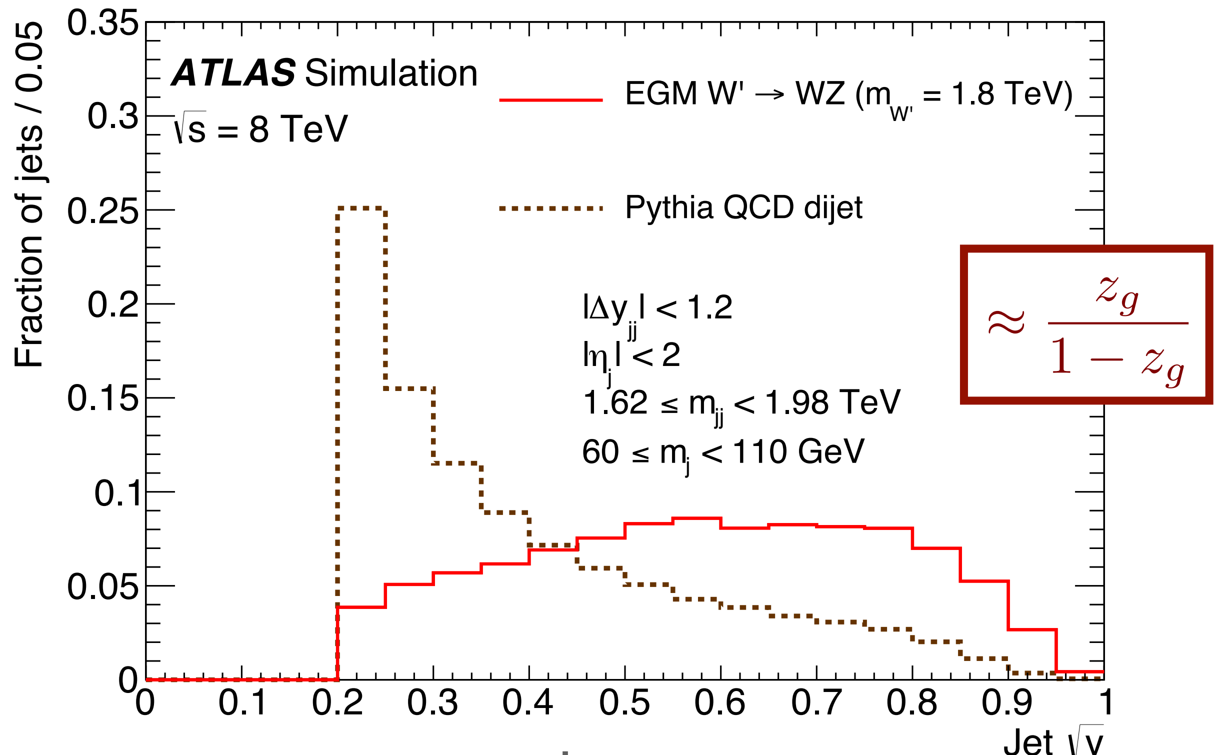
Groomed angular-ordered clustering tree:



cf.



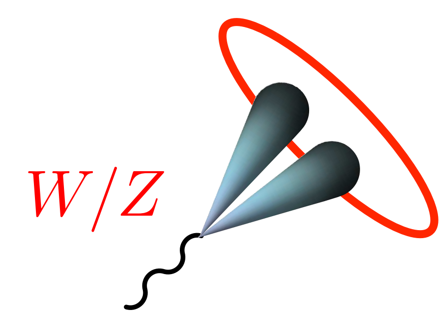
$$\frac{2\alpha_s C_i}{\pi} \frac{d\theta}{\theta} \frac{dz}{z}$$



QCD-like ↔ W/Z-like

One soft subjet

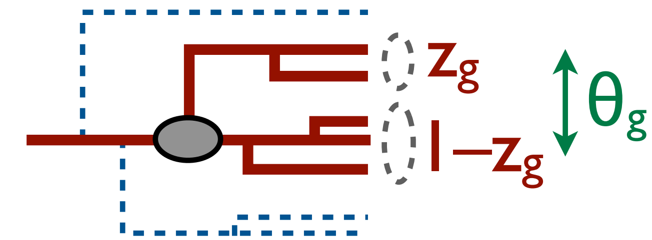
vs.



Balanced subjets

[Butterworth, Davison, Rubin, Salam, 0802.2470; see also Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Calculating Momentum Balance?



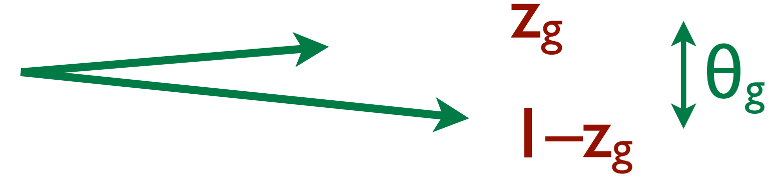
Collinear Unsafe

$$p(z_g)$$

Calculable
order-by-order in α_s

$$p(z_g|\theta_g)$$

vs.



[Larkoski, JDT, 1307.1699; Larkoski, Marzani, JDT, 1502.01719]

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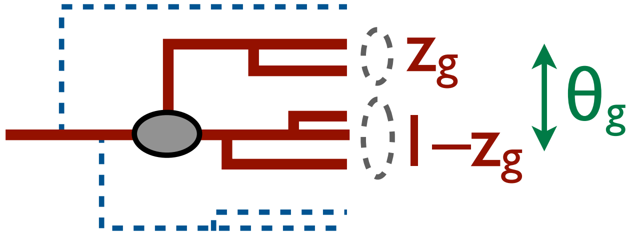
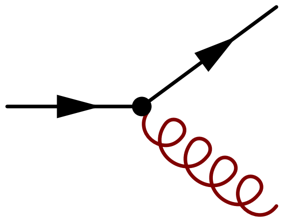
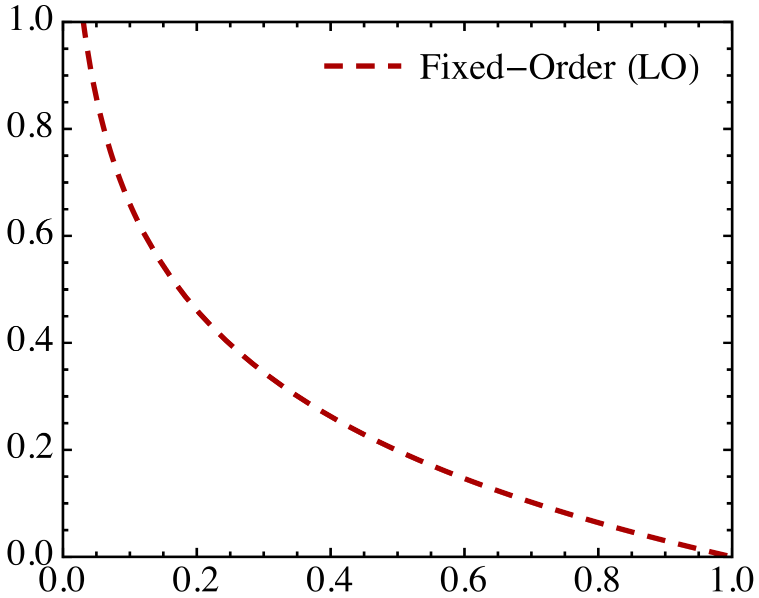


?!

Calculable order-by-order in α_s

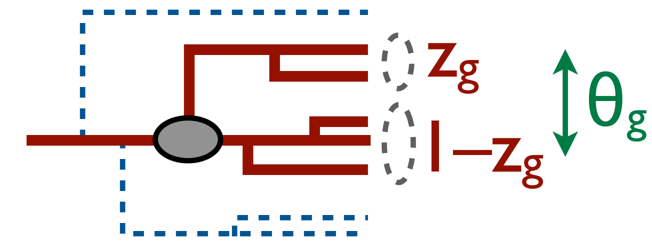
$$p(z_g) = \int \mathrm{d}\theta_g \, p(\theta_g) \, p(z_g|\theta_g)$$





[Larkoski, JDT, 1307.1699; Larkoski, Marzani, JDT, 1502.01719]

Calculating Momentum Balance?

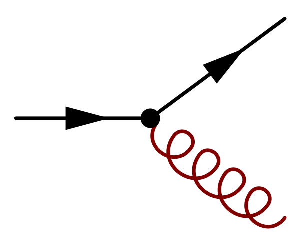


“Sudakov Safe”

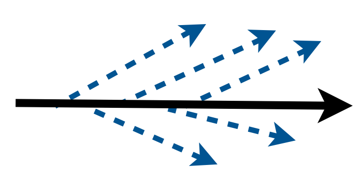
Calculable order-by-order in α_s

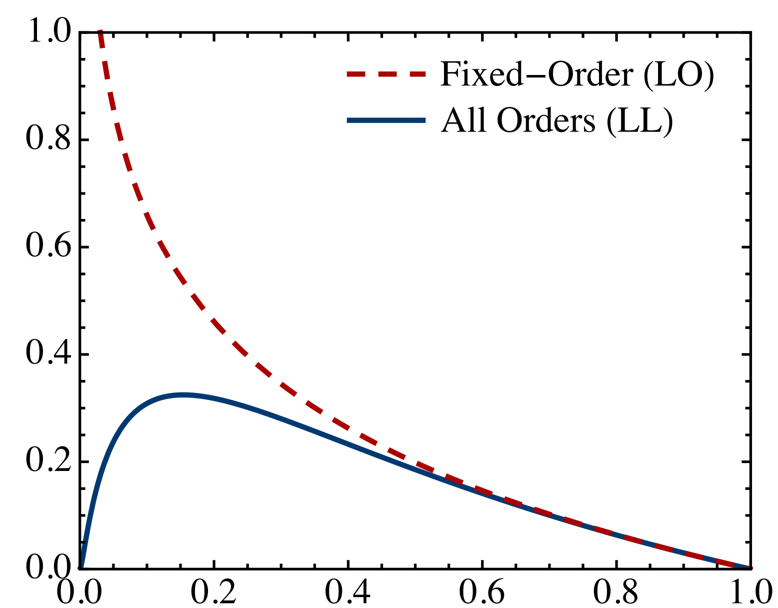
$$p(z_g) = \int d\theta_g \, p(\theta_g) \, p(z_g | \theta_g)$$

Form factor suppresses singularities at all orders in α_s



vs.

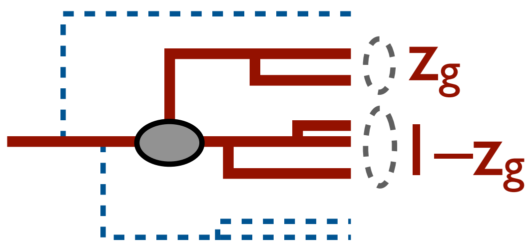




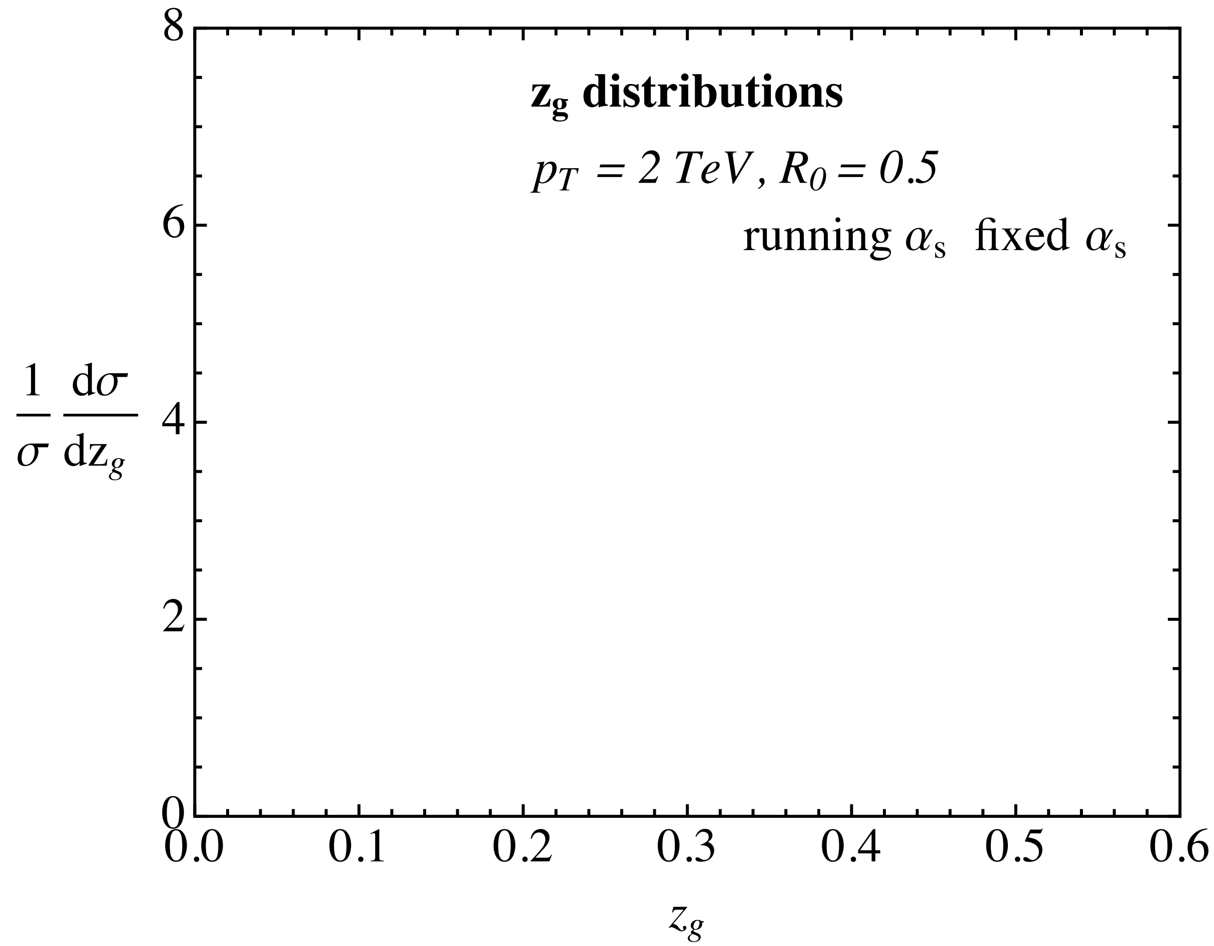
[Larkoski, JDT, 1307.1699; Larkoski, Marzani, JDT, 1502.01719]

First-Principles QCD

Soft Drop



$$z > z_{\text{cut}}\,\theta^{\beta}$$



q/g

$C_q = 4/3$
$C_g = 3$

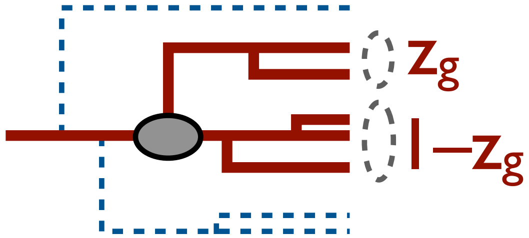
ATLAS 8 TeV
Diboson Search

More Grooming | Less Grooming

$\beta \to -\infty$ | $\beta < 0$ | $\beta = 0$ | $\beta > 0$ | $\beta \to \infty$

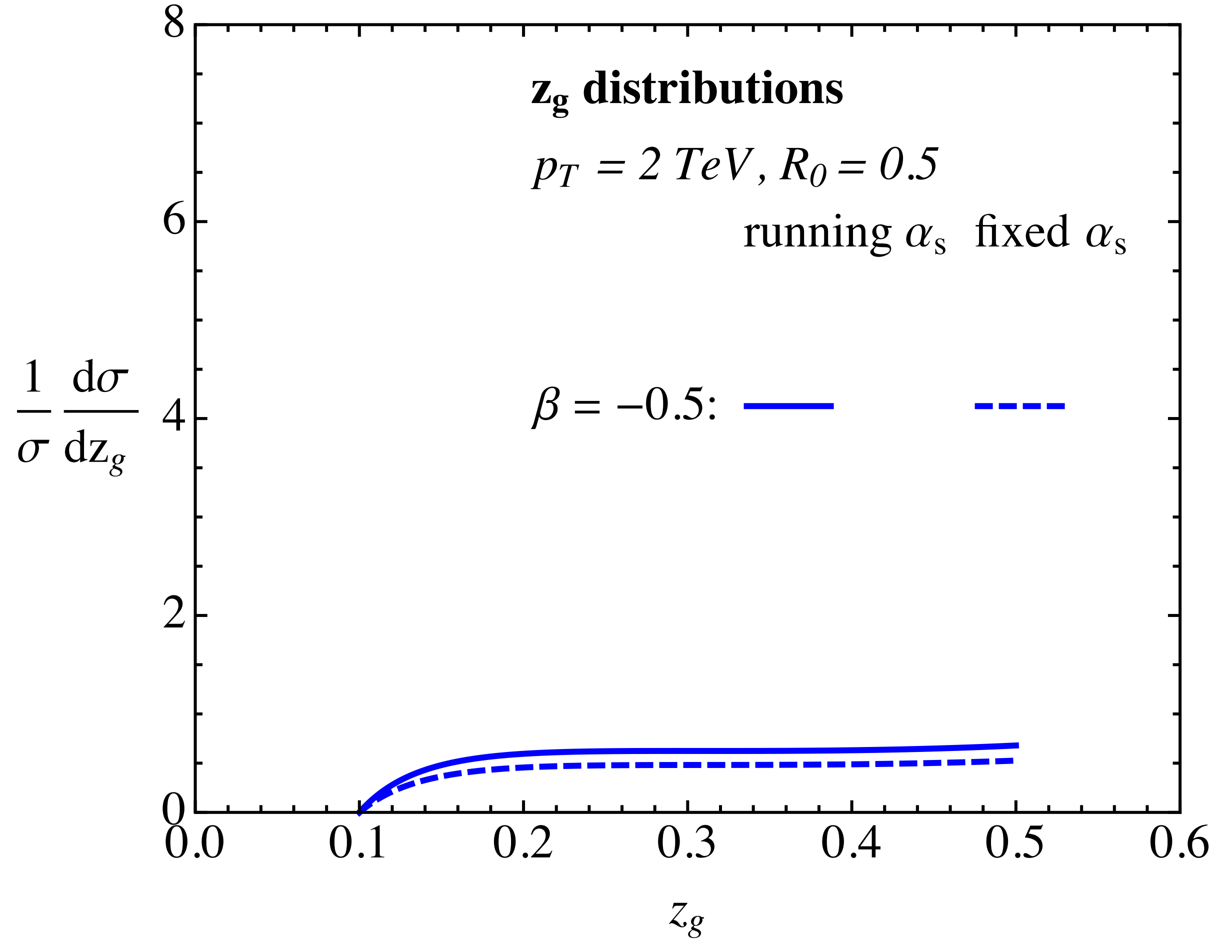
[Larkoski, Marzani, JDT, 1502.01719; using techniques in Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Larkoski, JDT, 1307.1699; Larkoski, Marzani, Soyez, JDT, 1402.2657]

Soft Drop



$$z > z_{\text{cut}}\,\theta^{\beta}$$

First-Principles QCD



q/g

$C_q = 4/3$
$C_g = 3$

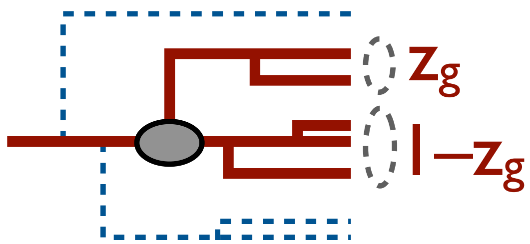
$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\,\frac{1}{z_g}\,\log\frac{z_g}{z_{\text{cut}}}$$

More Grooming | Less Grooming

$\beta \to -\infty$ | $\beta < 0$ | $\beta = 0$ | $\beta > 0$ | $\beta \to \infty$

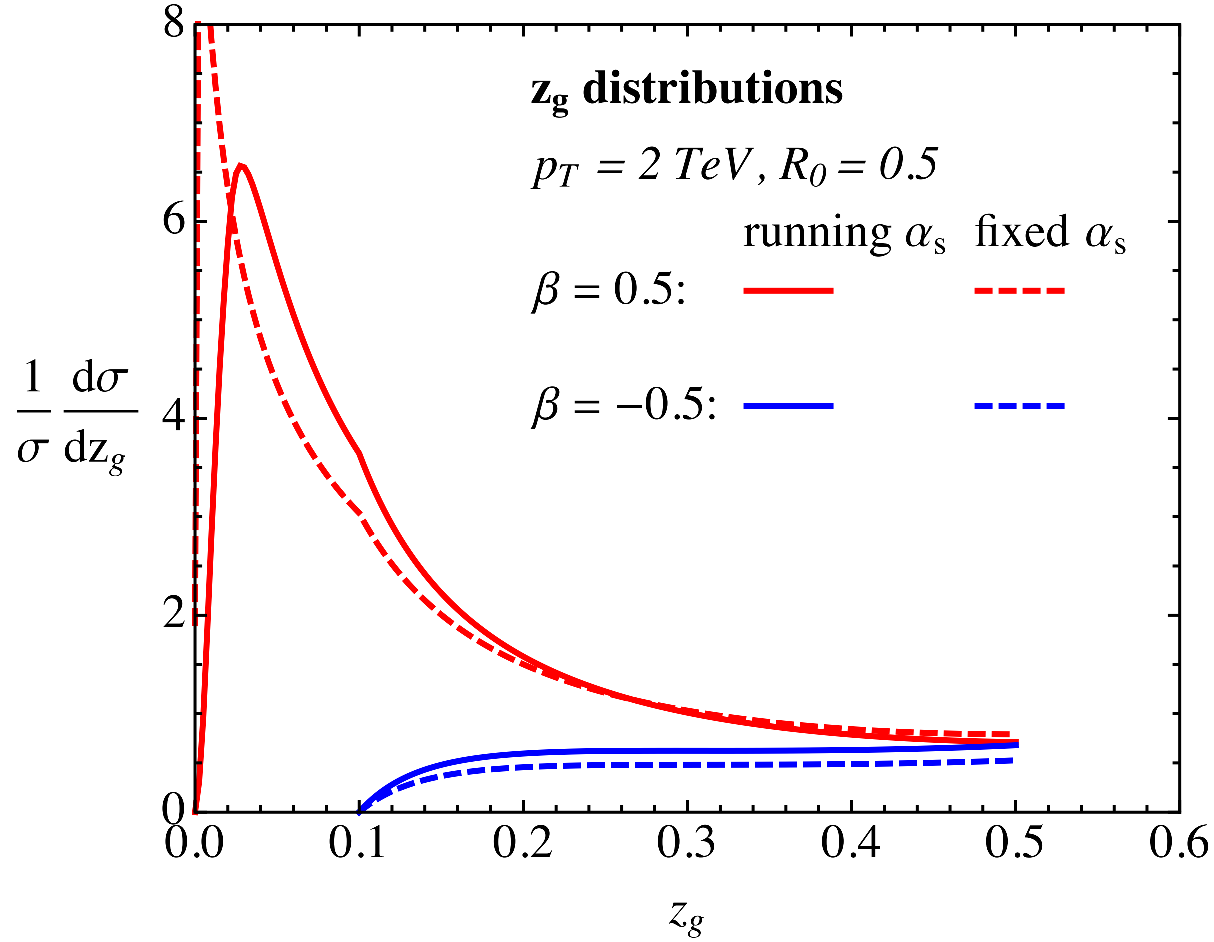
[Larkoski, Marzani, JDT, 1502.01719; using techniques in Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Larkoski, JDT, 1307.1699; Larkoski, Marzani, Soyez, JDT, 1402.2657]

Soft Drop



$$z > z_{\rm cut}\, \theta^\beta$$

First-Principles QCD



q/g

C_q = 4/3
C_g = 3

$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\frac{1}{z_g}\log\frac{z_g}{z_{\rm cut}}$$

$$\simeq \sqrt{\frac{\alpha_s C_i}{\beta}}\frac{1}{z_g}$$

Beyond traditional perturbation theory (Sudakov safe)

More Grooming

Less Grooming

β → −∞

β < 0

β = 0

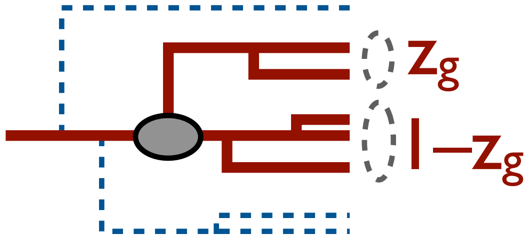
β > 0

β → ∞

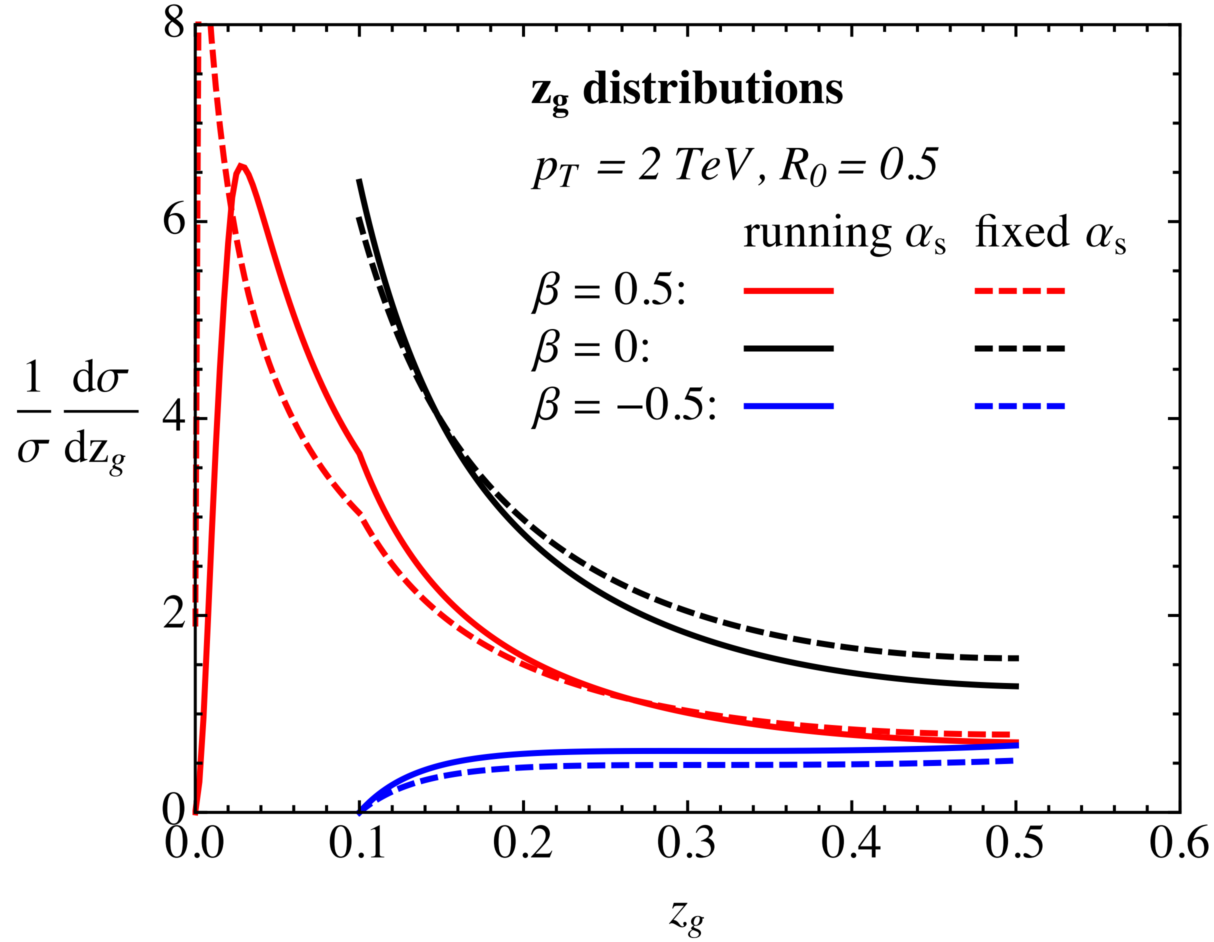
[Larkoski, Marzani, JDT, 1502.01719; using techniques in Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Larkoski, JDT, 1307.1699; Larkoski, Marzani, Soyez, JDT, 1402.2657]

First-Principles QCD

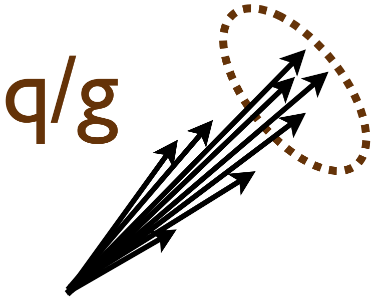
Soft Drop



$$z > z_{\text{cut}}\,\theta^{\beta}$$



q/g



$C_q = 4/3$

$C_g = 3$

$$\simeq \frac{2\alpha_s C_i}{\pi|\beta|}\,\frac{1}{z_g}\log\frac{z_g}{z_{\text{cut}}} \qquad \simeq \frac{1}{z_g}\ (!) \qquad \simeq \sqrt{\frac{\alpha_s C_i}{\beta}}\,\frac{1}{z_g}$$

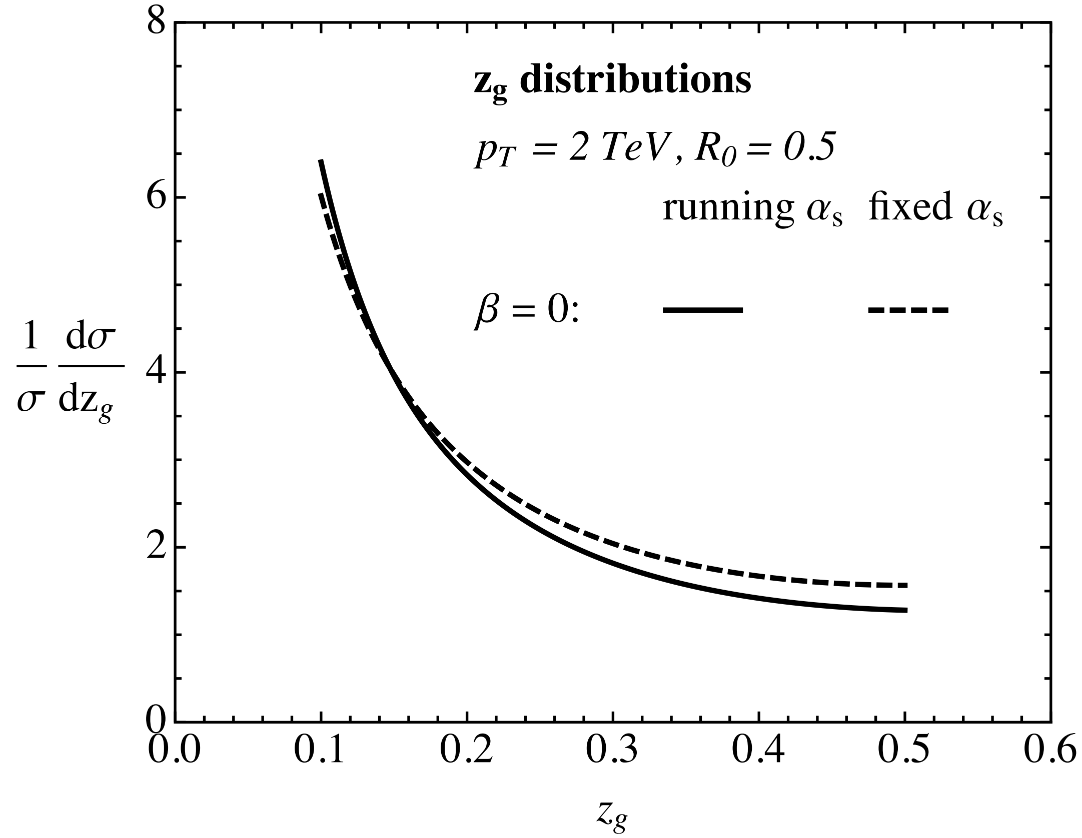
Beyond traditional perturbation theory (Sudakov safe)

More Grooming | Less Grooming

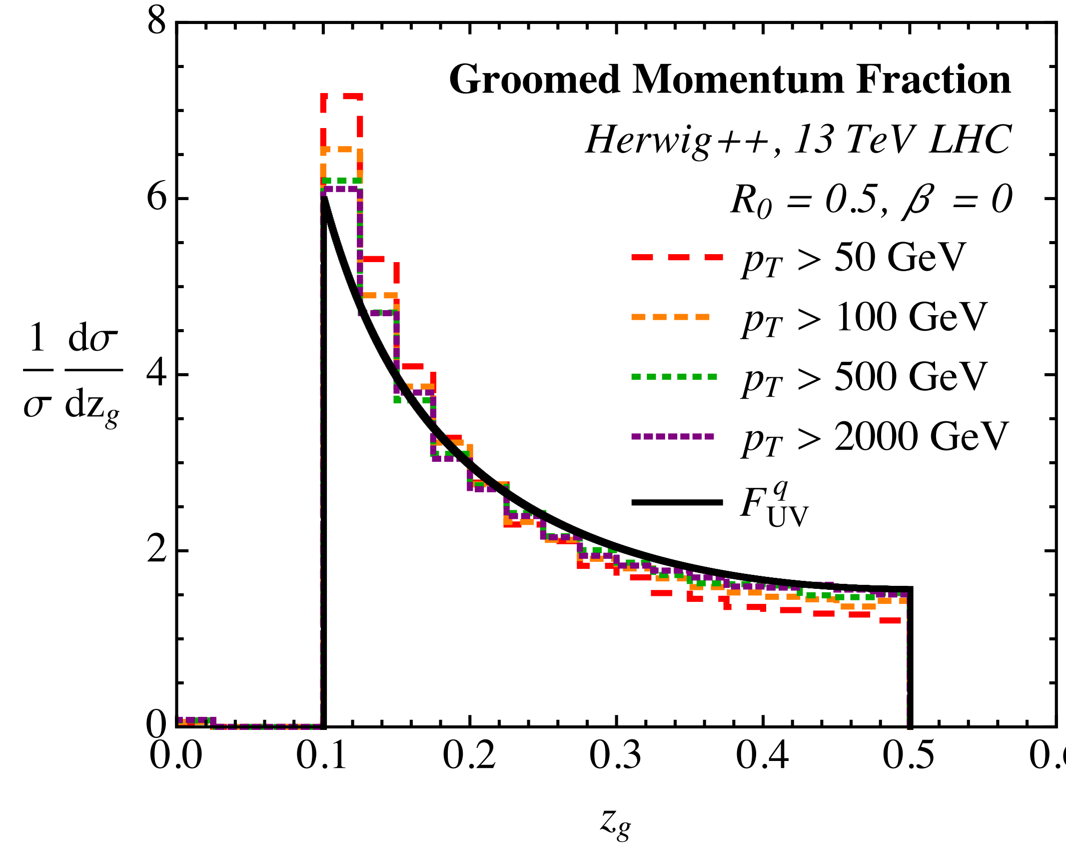
$\beta \to -\infty$ | $\beta < 0$ | $\beta = 0$ | $\beta > 0$ | $\beta \to \infty$

[Larkoski, Marzani, JDT, 1502.01719; using techniques in Dasgupta, Fregoso, Marzani, Salam, 1307.0007; Larkoski, JDT, 1307.1699; Larkoski, Marzani, Soyez, JDT, 1402.2657]

First-Principles QCD



Simulated LHC Data

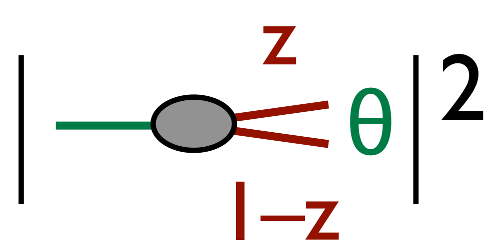


Core Feature of QCD: $\simeq \dfrac{1}{z_g}$

≈ independent of α_s (!)
≈ independent of jet energy/radius
≈ same for quarks/gluons

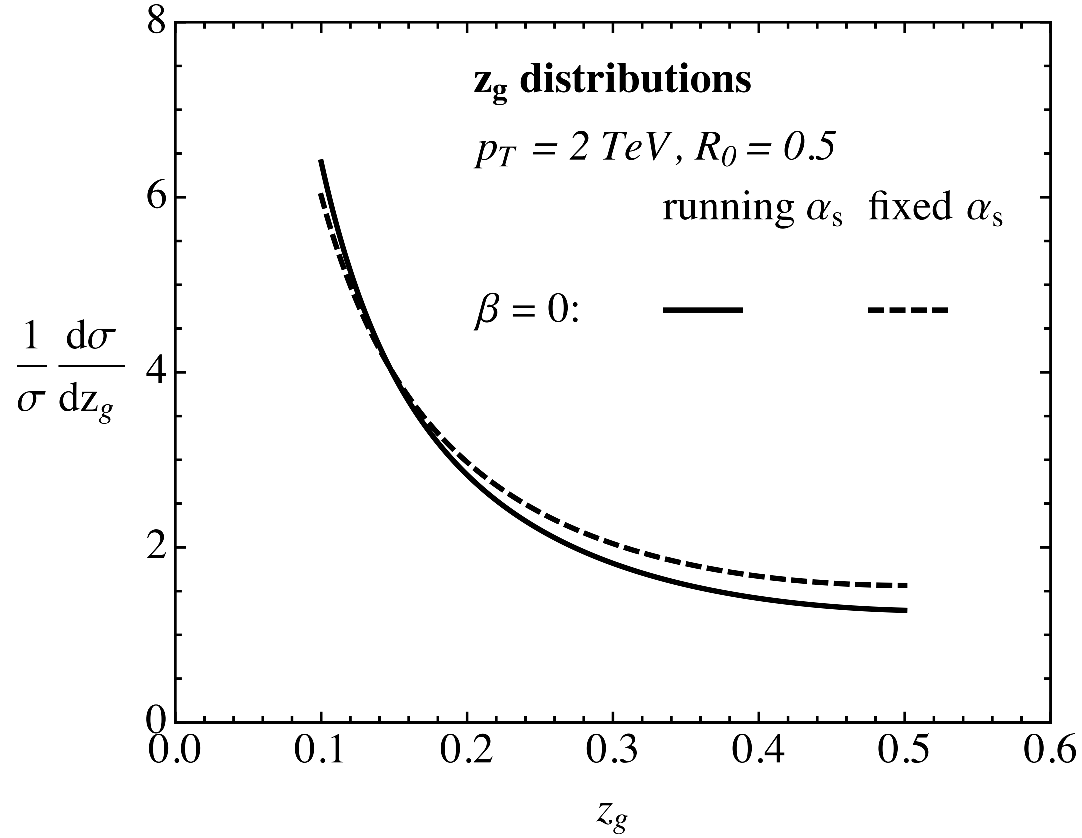
$$\updownarrow$$

$$dP_{i\to ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

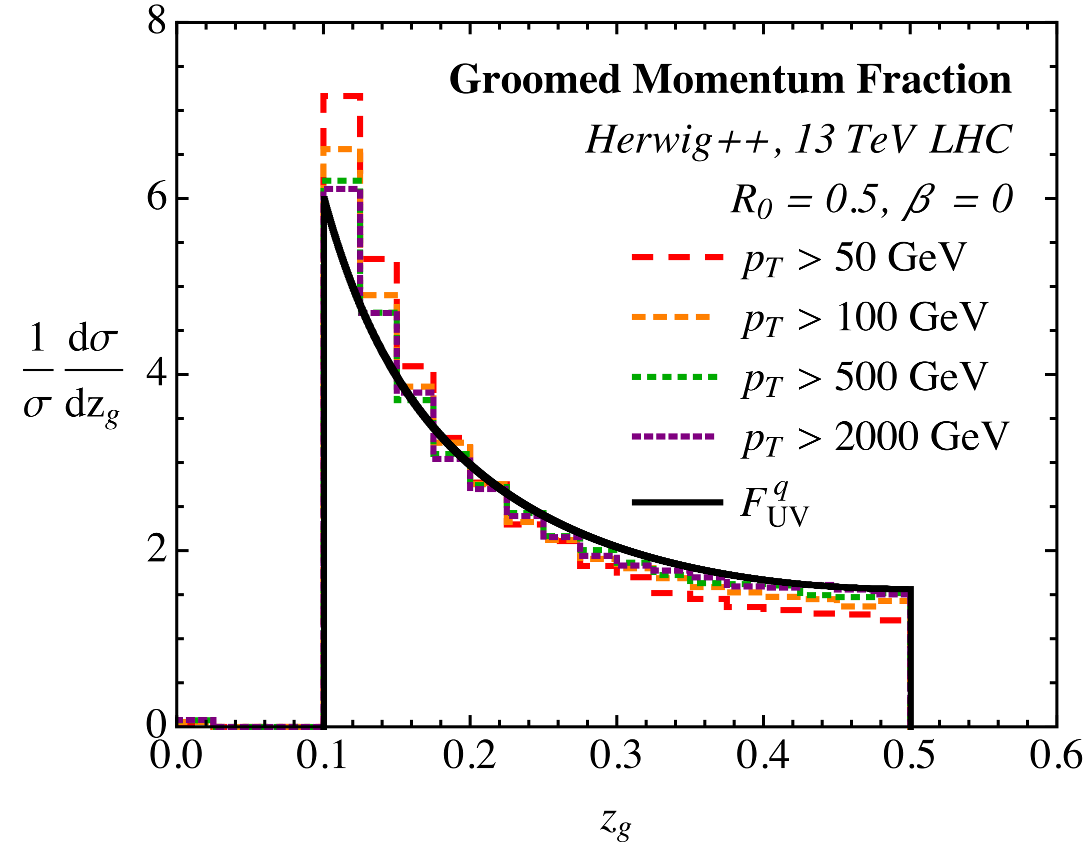
cf. 

[Larkoski, Marzani, JDT, 1502.01719; using Larkoski, JDT, 1307.1699]

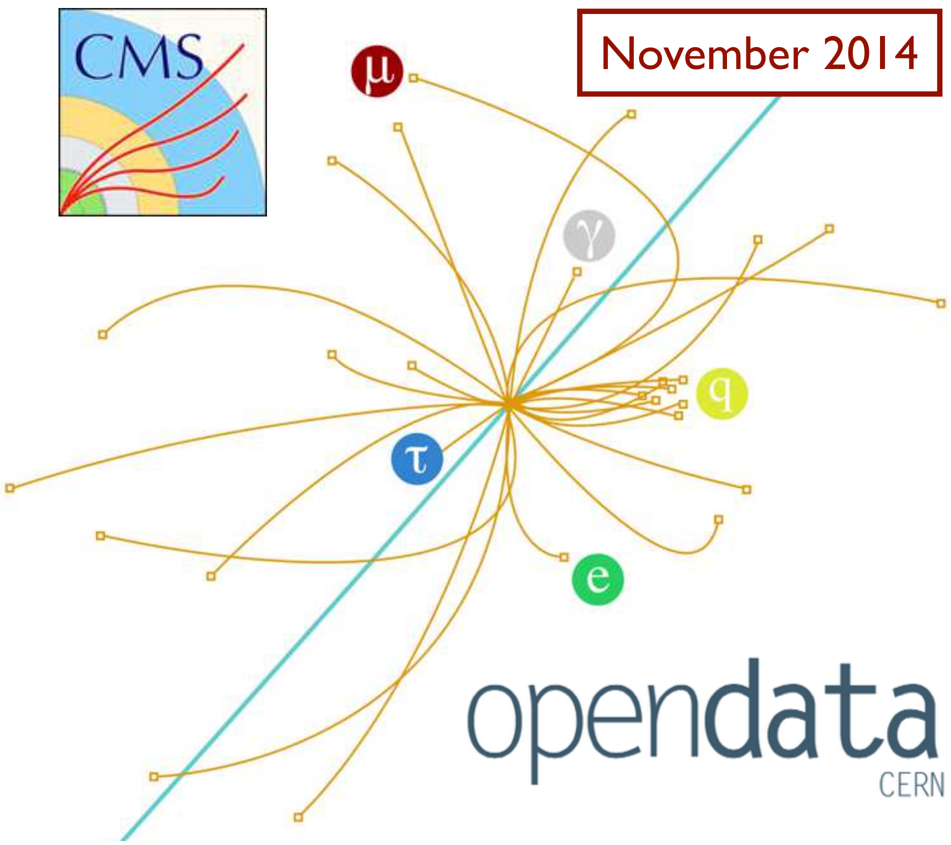
First-Principles QCD



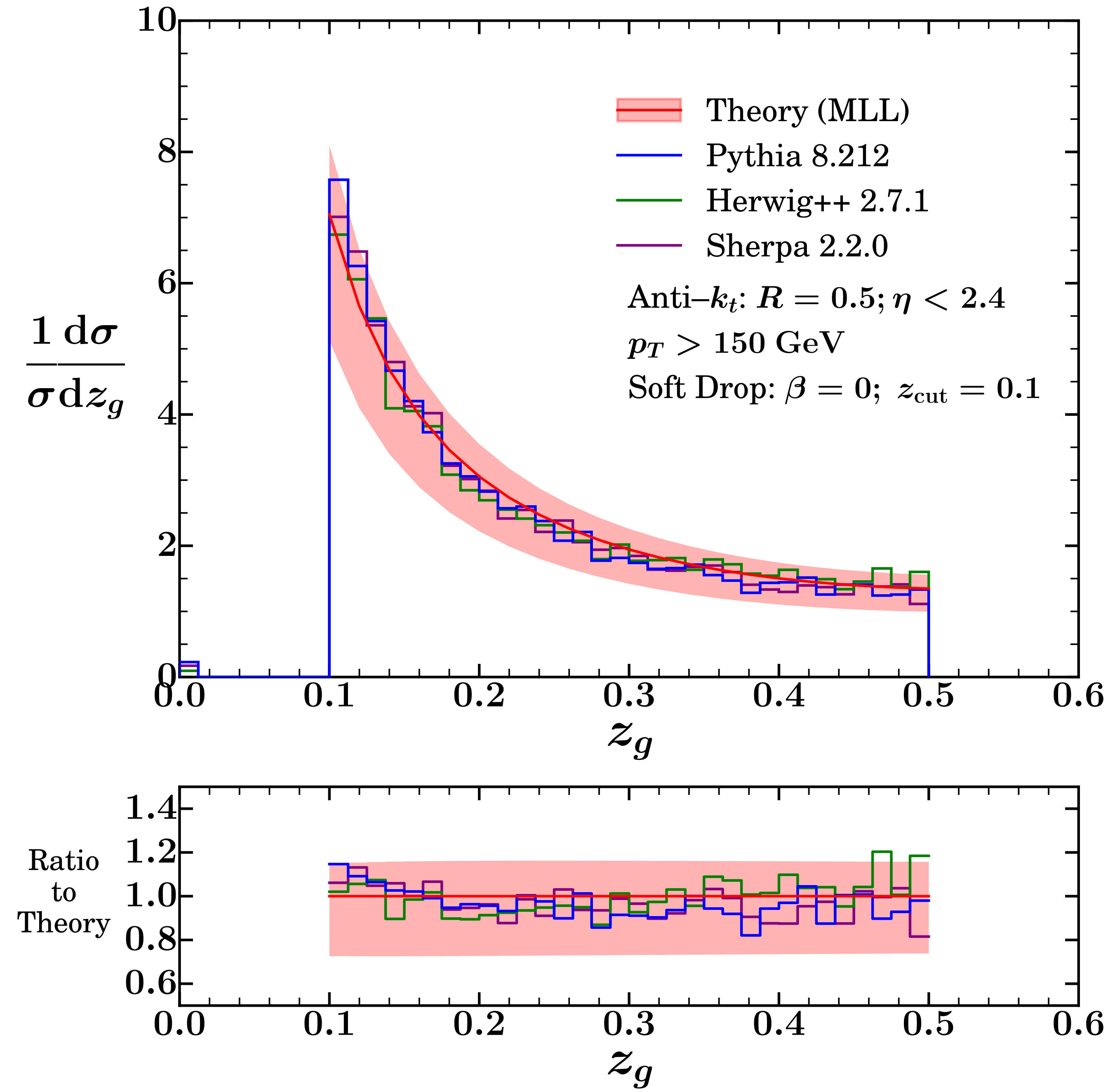
Simulated LHC Data

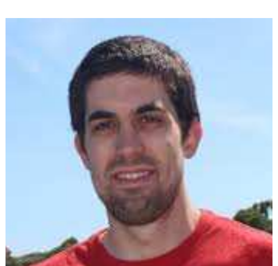
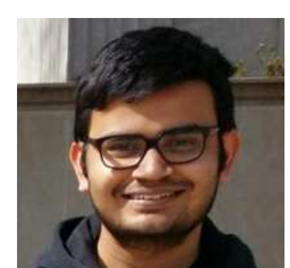


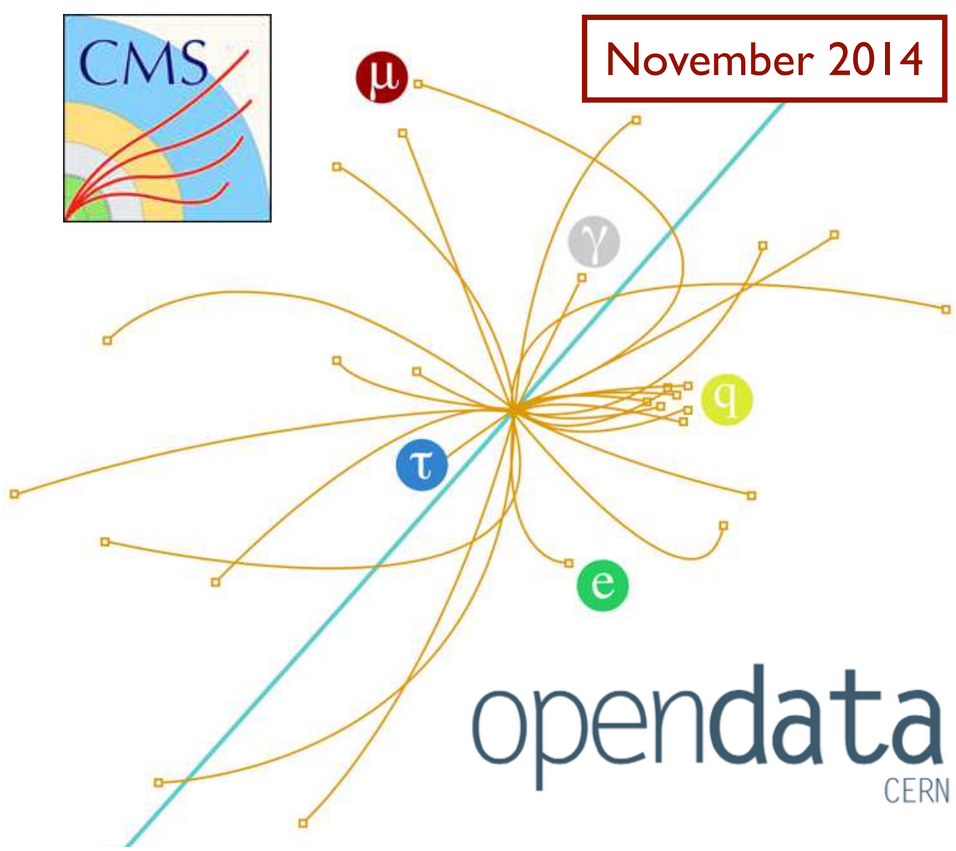
Actual LHC Data?



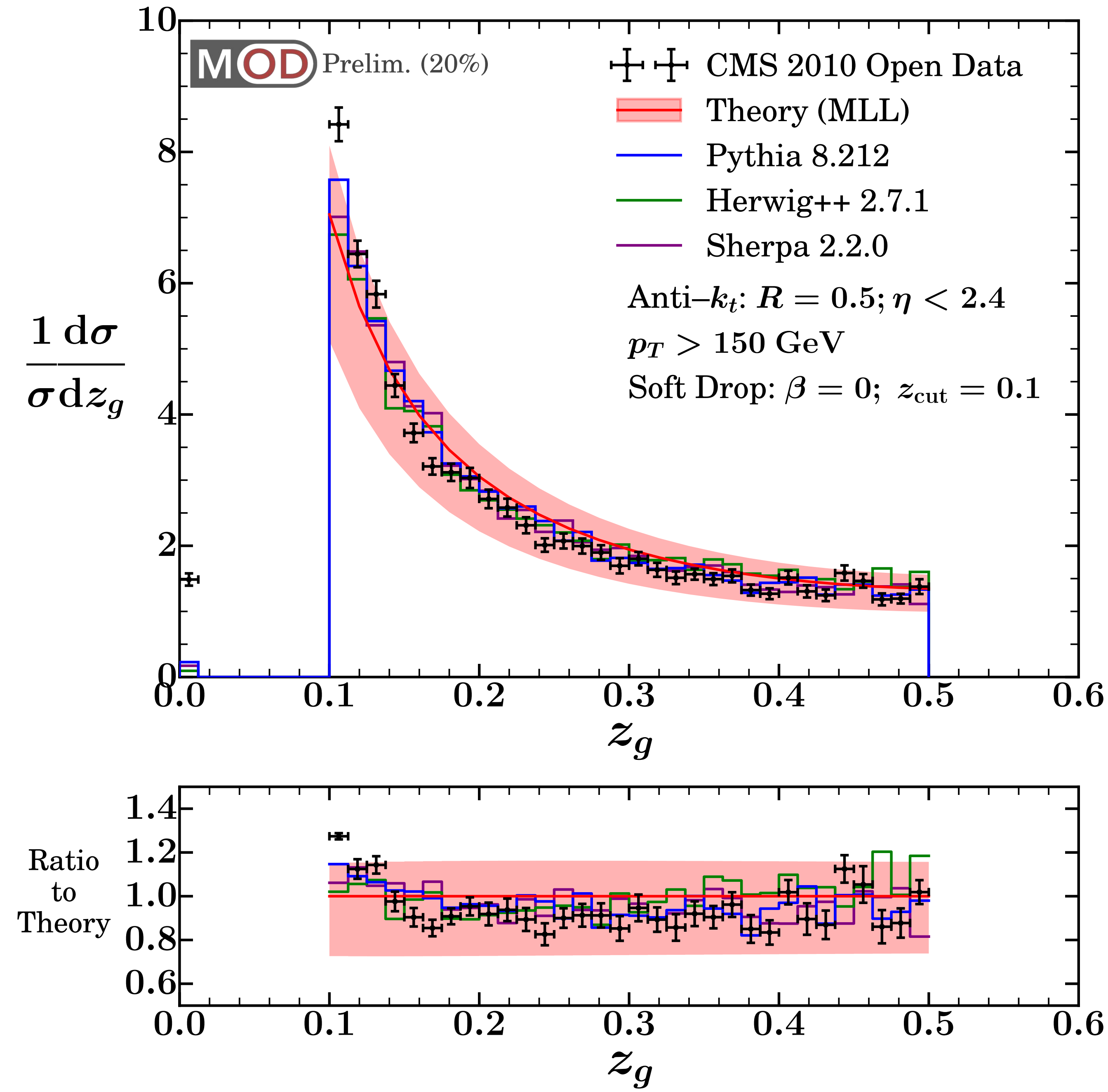
CMS 2010:
Unique, low pileup data set



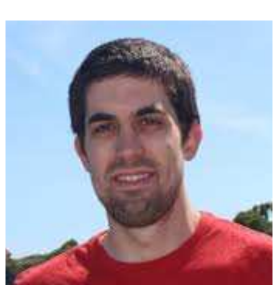
Andrew Larkoski	Simone Marzani	Alexis Romero	**Aashish Tripathee**	Wei Xue	CMS advice from Sal Rappoccio
					



CMS 2010:
Unique, low pileup data set



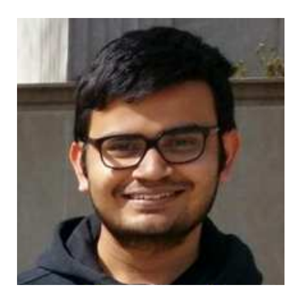
Andrew Larkoski



Simone Marzani

Alexis Romero

Aashish Tripathee

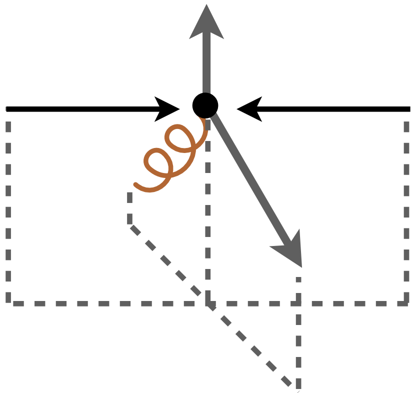


Wei Xue

CMS advice from
Sal Rappoccio

Substructure from First Principles

Probing the Core of QCD



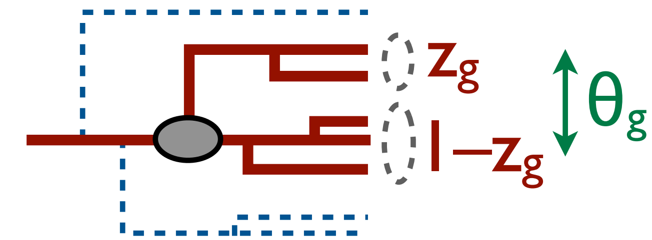
Back to the Future

New calculational technique to extend validity of perturbative quantum field theory

$$p(z_g) = \int \mathrm{d}\theta_g \, p(\theta_g) \, p(z_g|\theta_g)$$

Connections to old ideas?

1. Version of PS/ME Matching



$$p(z_g) = \int \mathrm{d}\theta_g \, \overset{\simeq\text{PS}}{p(\theta_g)} \, \overset{\simeq\text{ME}}{p(z_g|\theta_g)}$$

$$p(\theta_g) \simeq \frac{\mathrm{d}}{\mathrm{d}\theta_g} \exp\left[-\frac{\alpha_s C_i}{\pi}\left(\beta \log^2 \frac{1}{\theta_g} + 2 \log \frac{1}{\theta_g} \log \frac{1}{2\, z_{\text{cut}}}\right)\right]$$

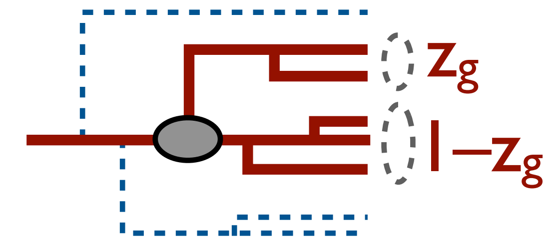
$$p(z_g|\theta_g) \simeq \frac{1}{\text{norm}} \frac{1}{z_g} \Theta(z_g - z_{\text{cut}}\theta_g{}^{\beta})$$

$$p(z_g) \simeq \sqrt{\frac{\alpha_s C_i}{\beta}} \frac{1}{z_g} \exp\left[\frac{\alpha_s C_i}{\pi\beta} \log^2 \frac{1}{2 z_{\text{cut}}}\right] \operatorname{erfc}\left[\sqrt{\frac{\alpha_s C_i}{\pi\beta}} \log \frac{1}{\min[2 z_{\text{cut}}, 2 z_g]}\right]$$

$$\Rightarrow \frac{1}{\text{norm}} \frac{1}{z_g} \Theta(z_g - z_{\text{cut}}) \quad (\beta = 0)$$

[Larkoski, Marzani, JDT, 1502.01719; using Larkoski, JDT, 1307.1699; Larkoski, Marzani, Soyez, JDT, 1402.2657]

2. Renormalization Group Flow

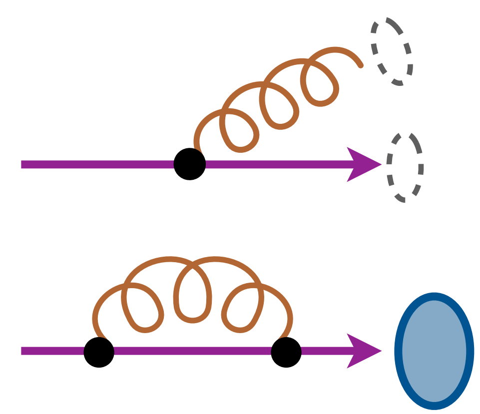


Collinear Unsafe?

Absorb singularities into universal nonperturbative function (cf. PDFs)

$$\frac{d\sigma}{dz_g} = \Big(\textit{fragmentation function} \Big) + \alpha_s \Big(\textit{collinear singularities} \Big) + \mathcal{O}(\alpha_s^2)$$

absorb



$$\mu \frac{\partial}{\partial \mu} F_i(z_g;\mu) \simeq \frac{\alpha_s C_i}{\pi} \Big(p(z_g) - F_i(z_g;\mu) \Big)$$

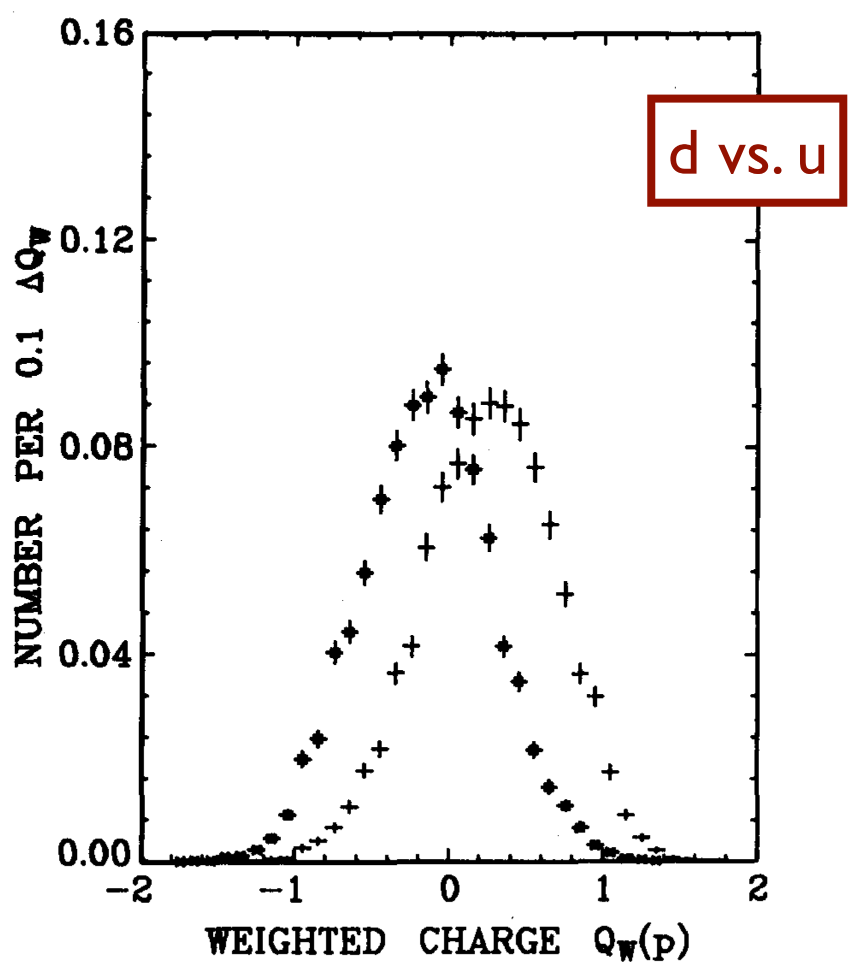
UV fixed point

[Larkoski, Marzani, JDT, 1502.01719]

Generalized Fragmentation Functions

e.g. Weighted Jet Charge…

$$Q_W(p) = \sum_i z_i^p q_i$$

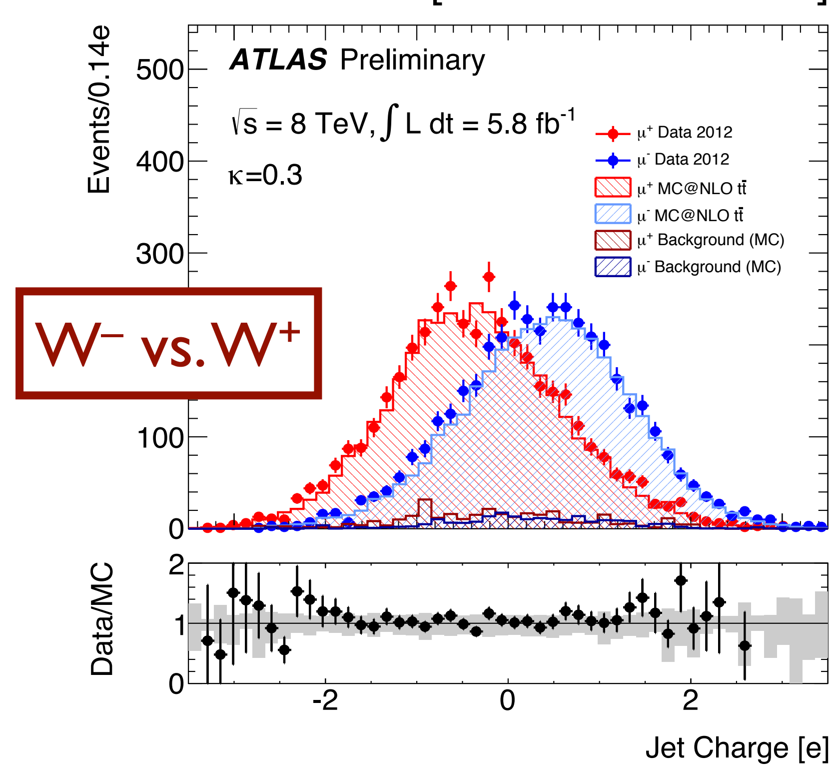


[Feynman, Field, 1978]

…on Firm Theoretical Ground

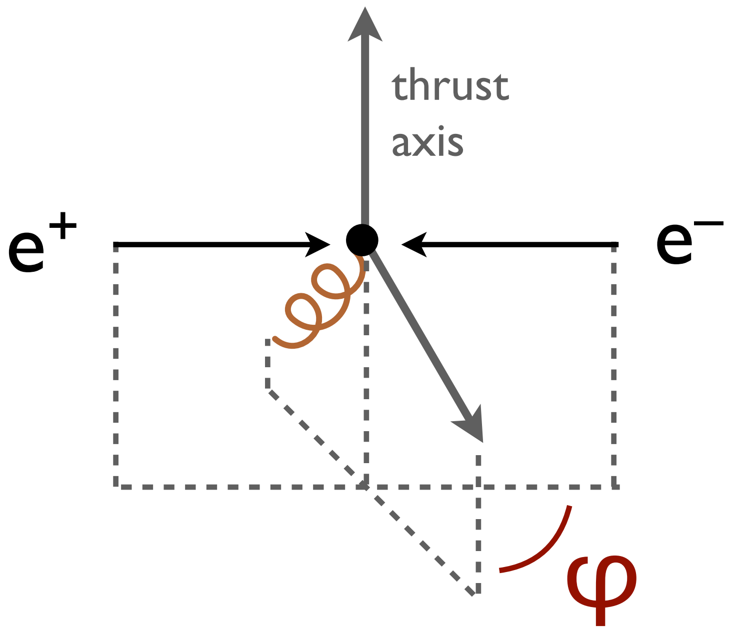
$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} D_i(Q,\kappa,\mu) = \frac{1}{2}\sum_j \int \mathrm{d}Q_1\,\mathrm{d}Q_2\,\mathrm{d}z\,\gamma_{ij}^D(z,\mu) \times D_j(Q_1,\kappa,\mu) D_{a(ij)}(Q_2,\kappa,\mu) \times \delta[Q - z^\kappa Q_1 - (1-z)^\kappa Q_2]$$

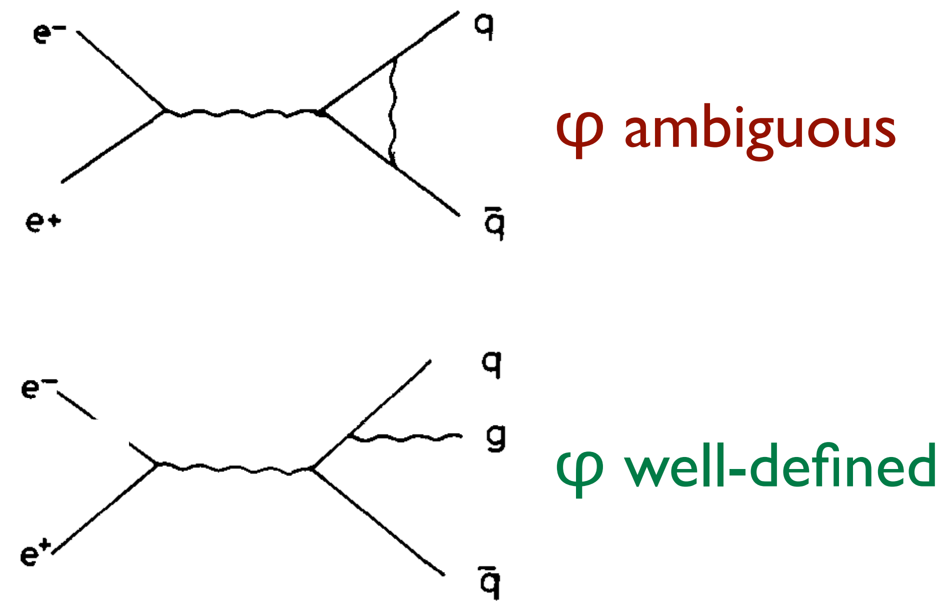
[ATLAS-CONF-2013-086]



[Krohn, Schwartz, Lin, Waalewijn, 1209.2421; Waalewijn, 1209.3019]
[see also Chang, Procura, JDT, Waalewijn, 1303.6637, 1306.6630; Larkoski, JDT, Waalewijn, 1408.3122]

3. Learning from our Elders





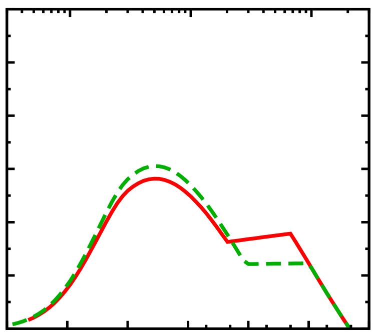
$$\frac{2\pi}{\sigma_0}\frac{d\sigma}{d\varphi} = 1 + O(\alpha_s(Q^2)) + \frac{\alpha_s(Q^2)}{\pi}\left(\tfrac{16}{3}\ln\tfrac{3}{2} - 2\right)\cos 2\varphi$$

Born cross section despite ambiguity (!)

Exploits generalized notion of "observable"

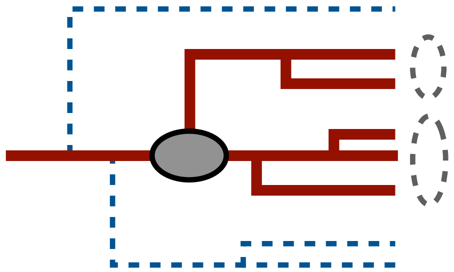
[Pi, Jaffe, Low, 1978; Kramer, Schierholz, Willrodt, 1978]

Summary



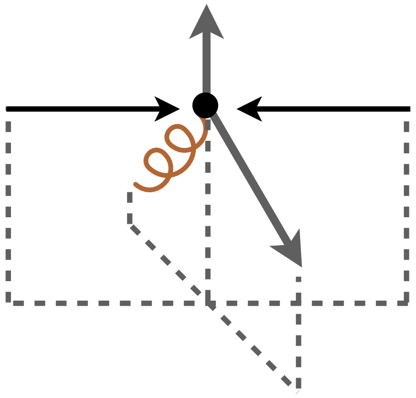
Substructure from First Principles

Growing catalog of observables, growing toolbox of approaches



Probing the Core of QCD

Exposing the universal singularity structure of gauge theories



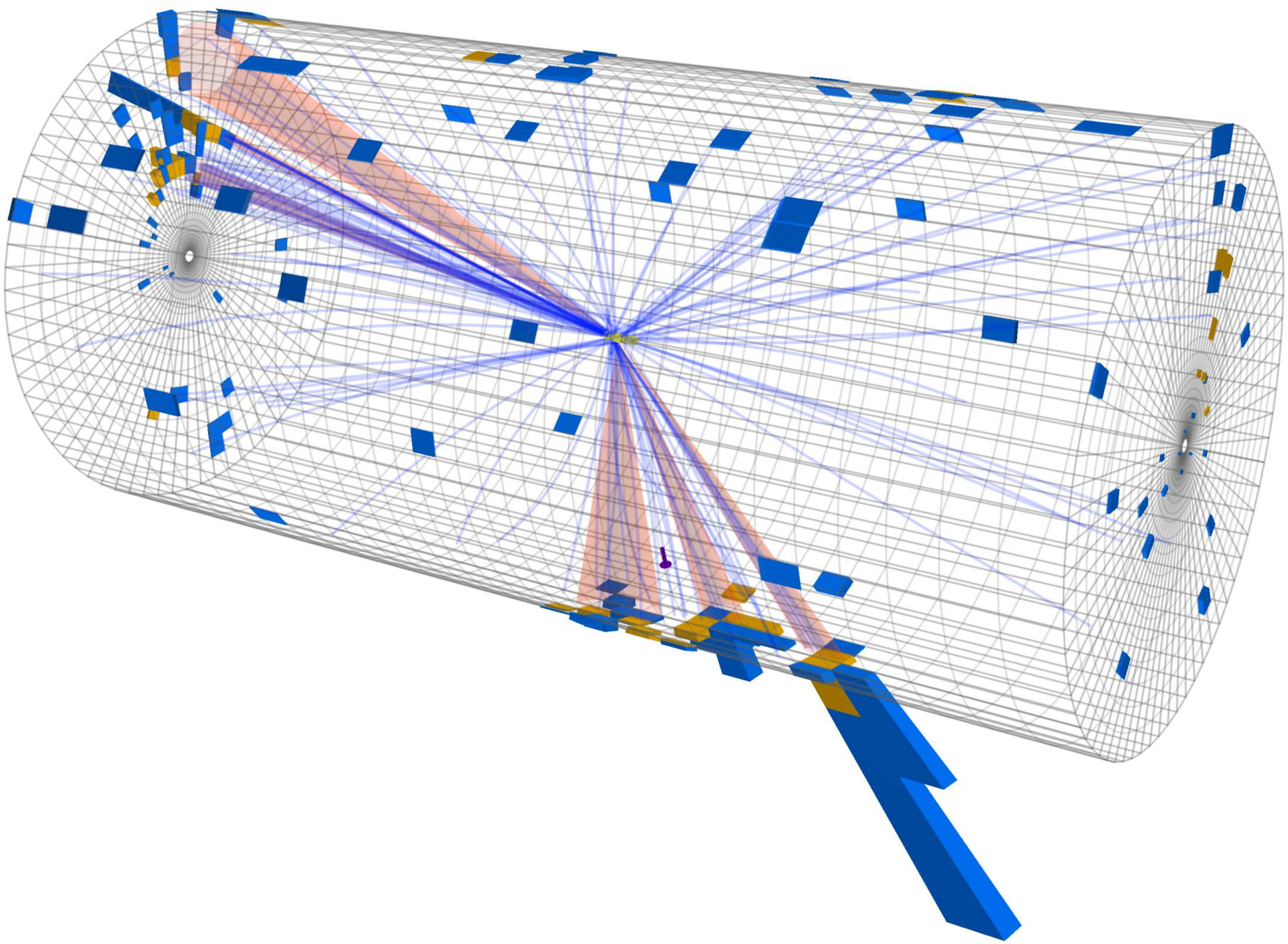
Back to the Future

Old/new ways to extend validity of perturbative quantum field theory

July 18–22, 2016

Backup Slides

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253



[CMS, 1506.03062]
[using Kaplan, Rehermann, Schwartz, Tweedie, 0806.0848; using Ellis, Vermilion, Walsh, 0903.5081, 0912.0033]

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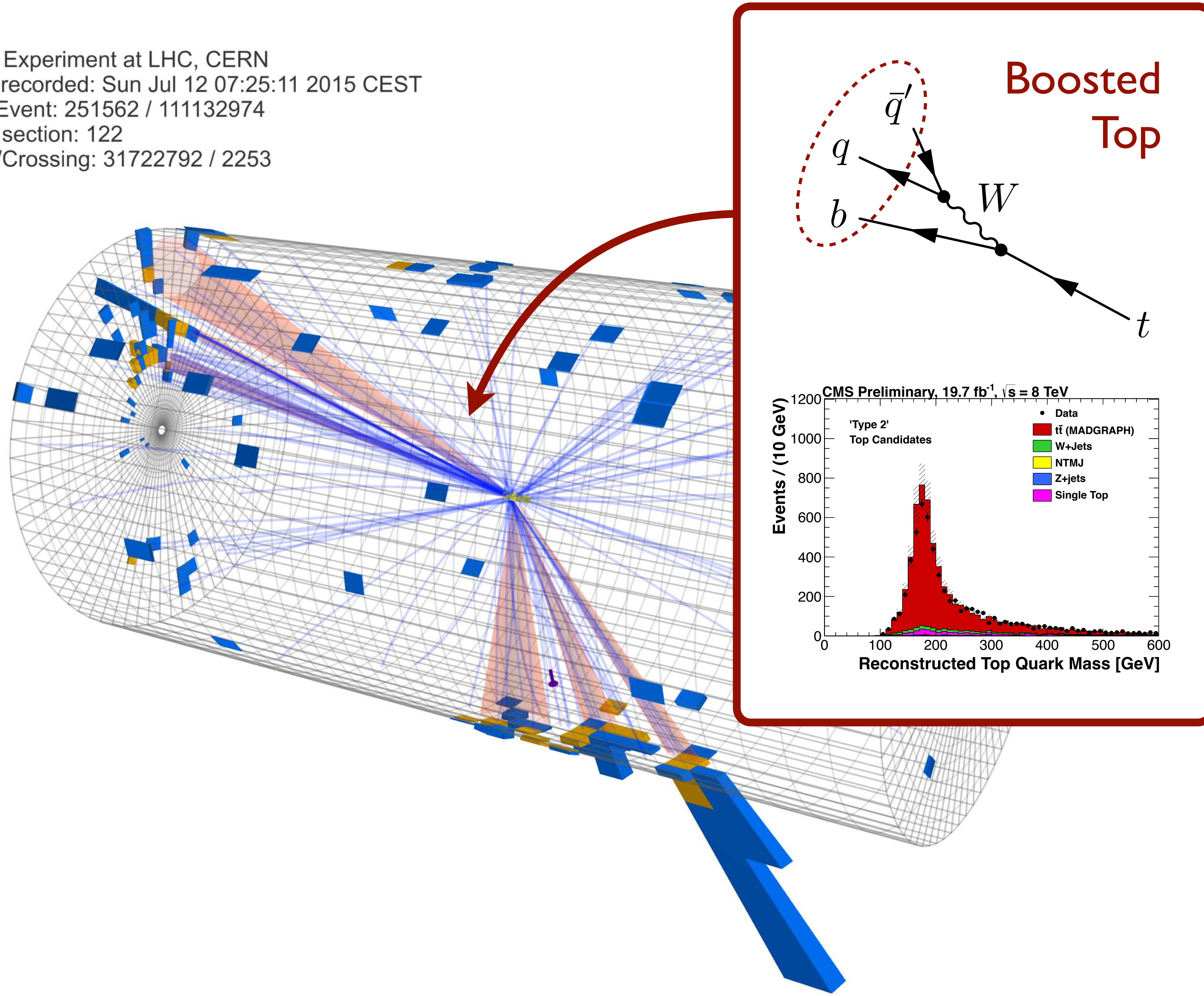
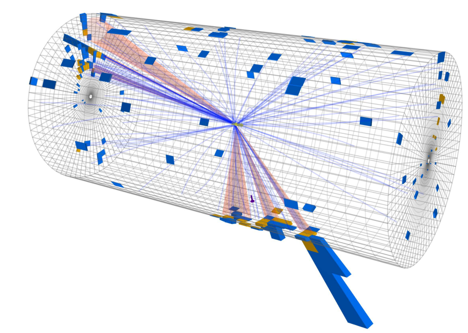
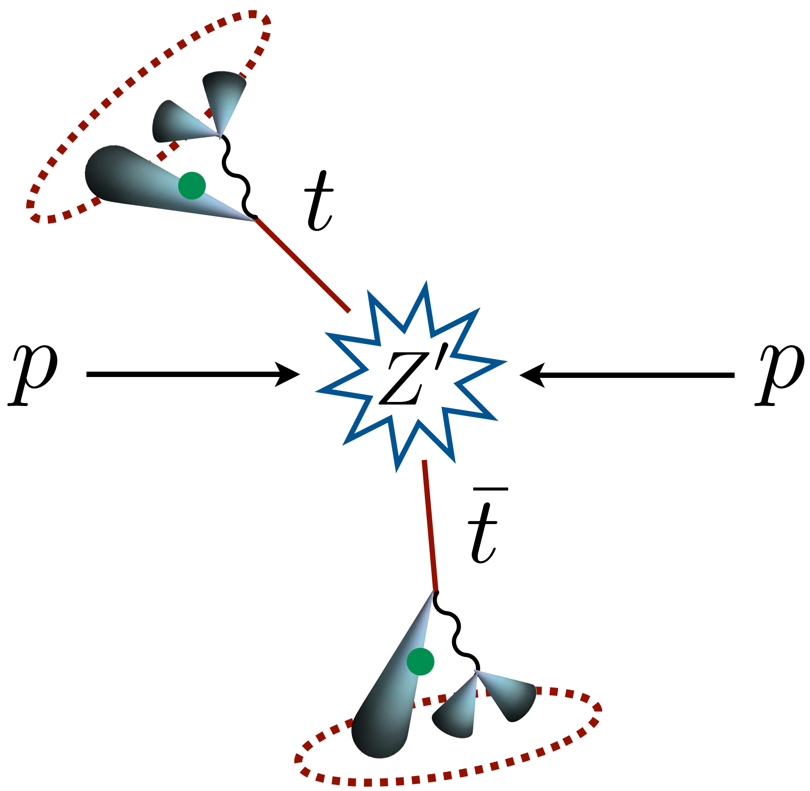
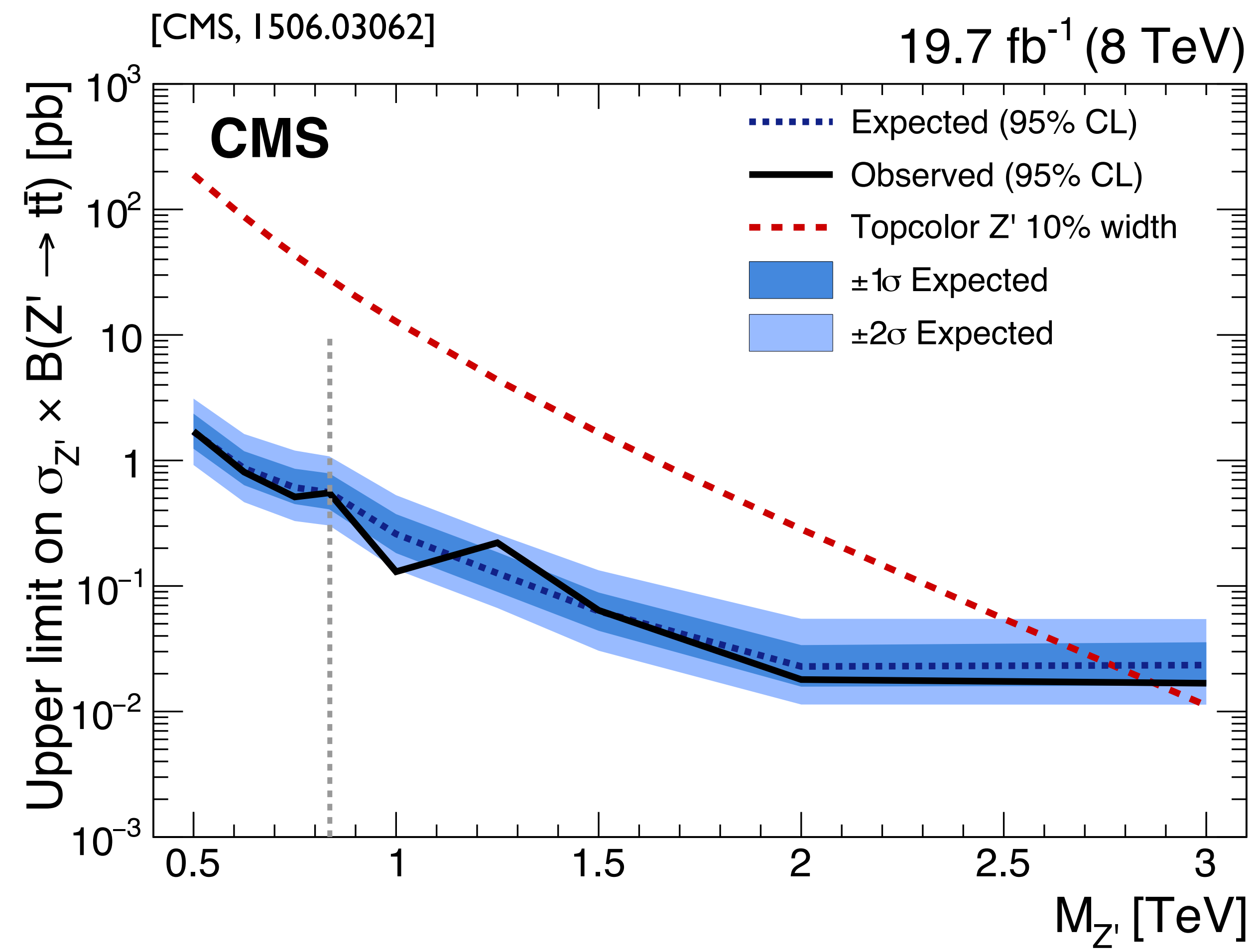


[CMS, 1506.03062]
[using Kaplan, Rehermann, Schwartz, Tweedie, 0806.0848; using Ellis, Vermilion, Walsh, 0903.5081, 0912.0033]

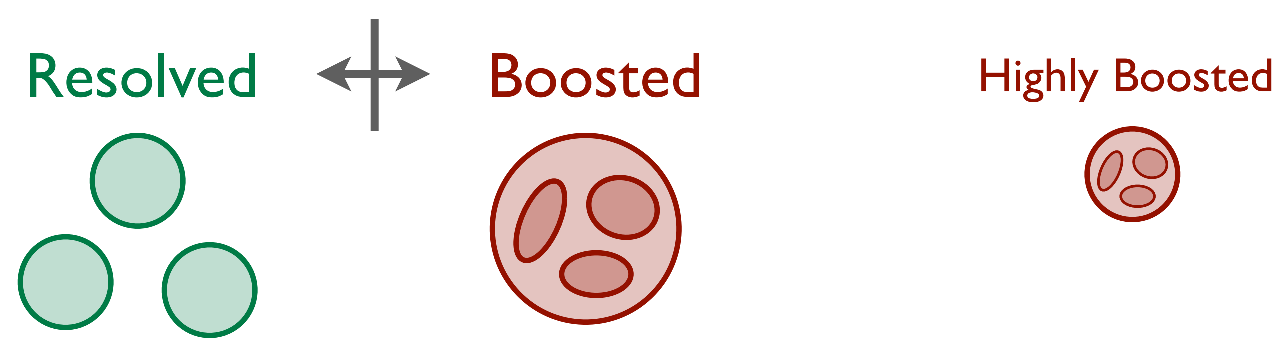
Welcome to the Boosted Regime

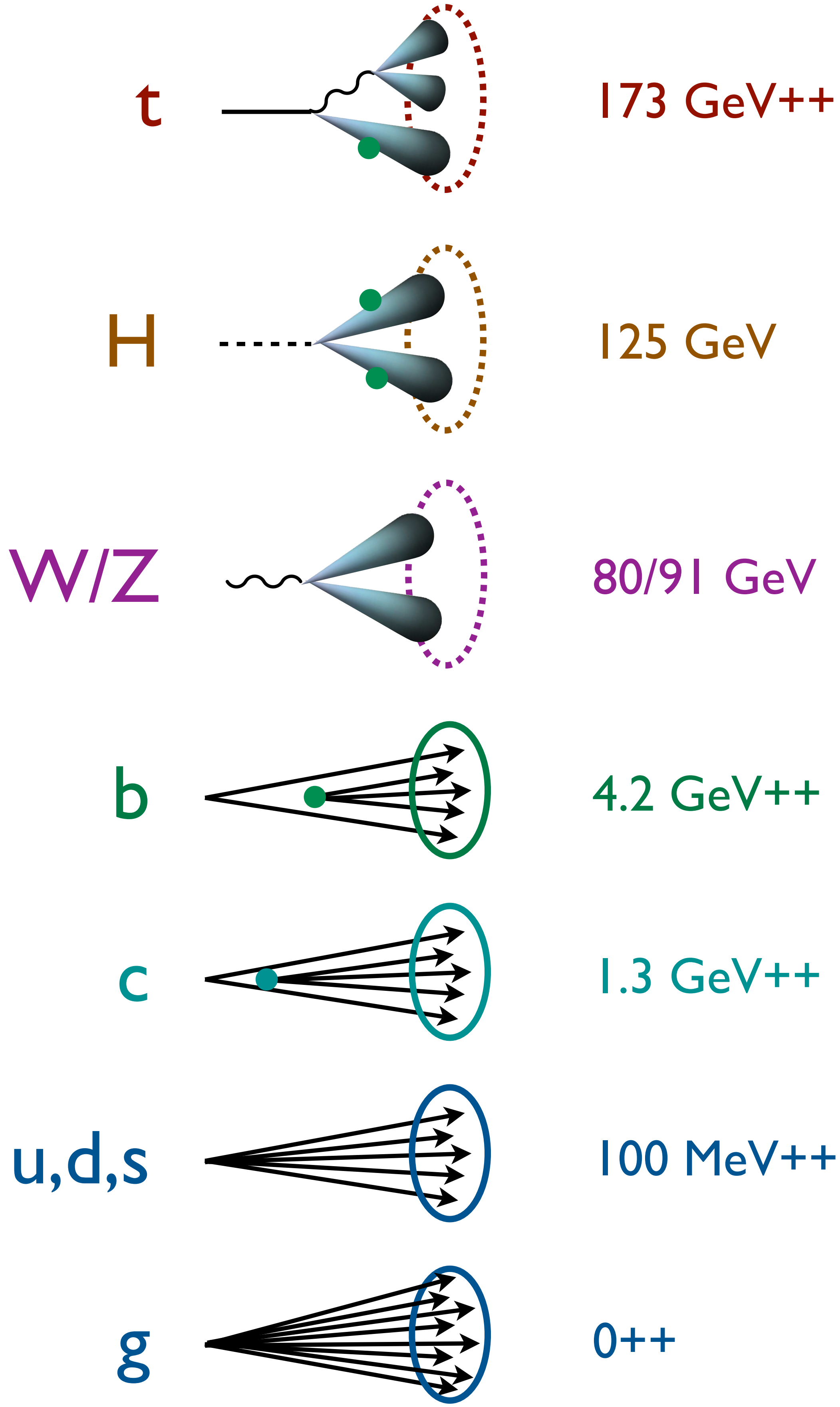




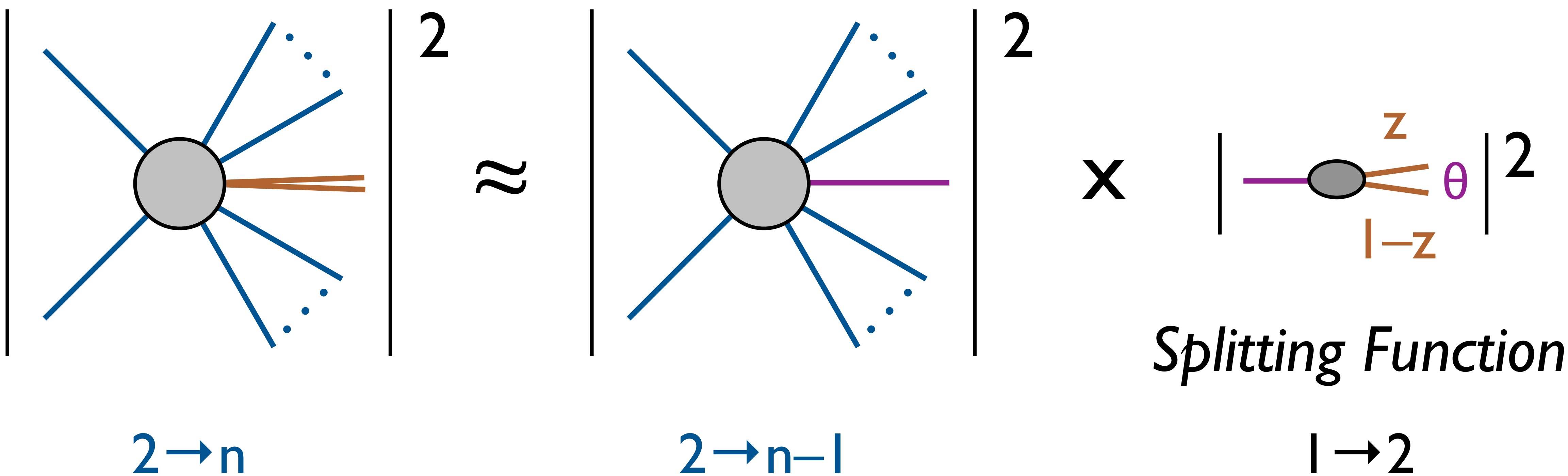


$$\Delta R \simeq \frac{2 m_{\text{top}}}{p_T}$$



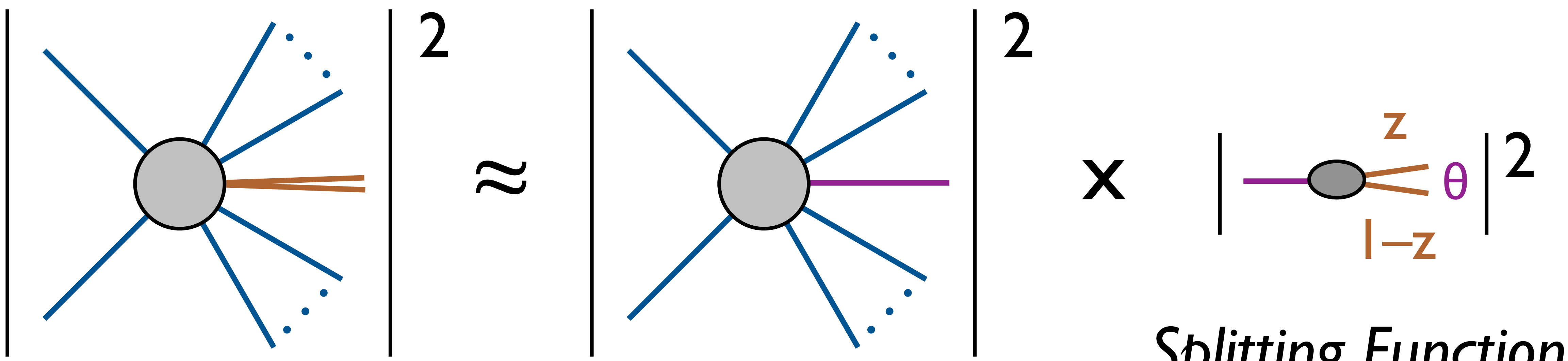

t
173 GeV++
H
125 GeV
W/Z
80/91 GeV
b
4.2 GeV++
c
1.3 GeV++
u,d,s
100 MeV++
g
0++

Textbook QCD: Universal Collinear Limit



$$\mathrm{d}P_{i\to jk} = \underbrace{\frac{\mathrm{d}\theta}{\theta}}_{\text{Collinear singularity}}\,\mathrm{d}z\,\underbrace{P_{i\to jk}(z)}_{\text{Altarelli-Parisi splitting function}}$$

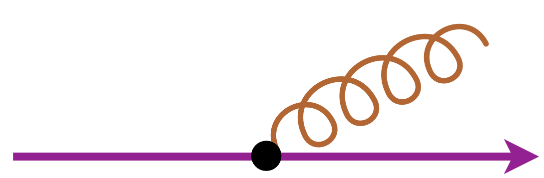
Textbook QCD: Universal Collinear Limit



Splitting Function

$2 \to n$ $\qquad$ $2 \to n-1$ $\qquad$ $1 \to 2$

For this talk:



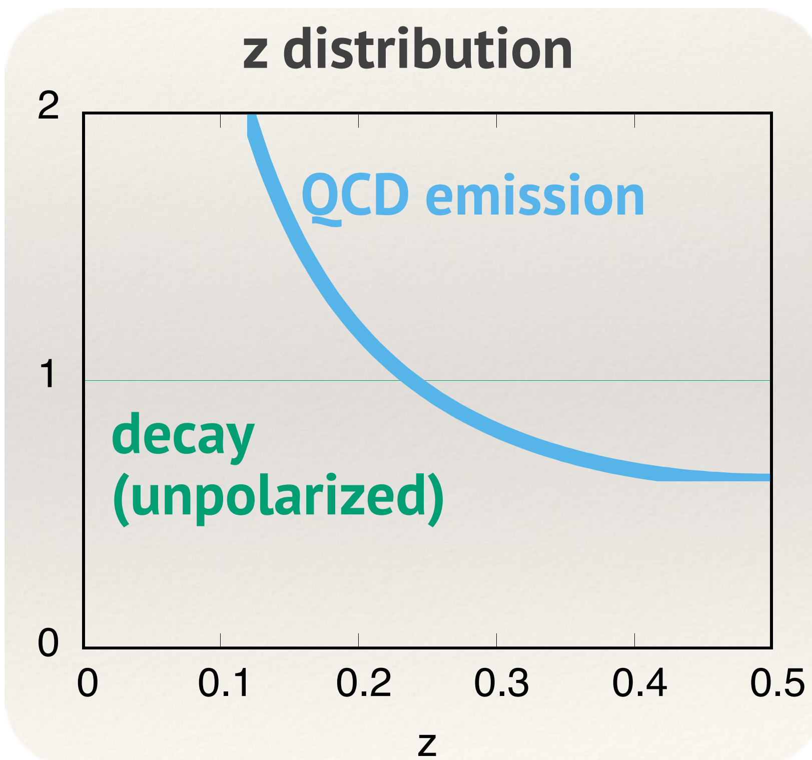
$C_q = 4/3$
$C_g = 3$

$$dP_{i \to ig} \simeq \frac{2\alpha_s}{\pi} C_i \underbrace{\frac{d\theta}{\theta}}_{\text{Collinear singularity}} \underbrace{\frac{dz}{z}}_{\text{Soft singularity}}$$

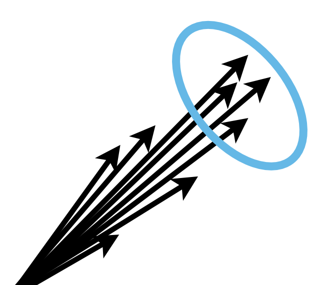
QCD Splitting Functions

Basis for DGLAP evolution of PDFs, parton shower generators, fixed-order subtractions, k_t jet clustering…

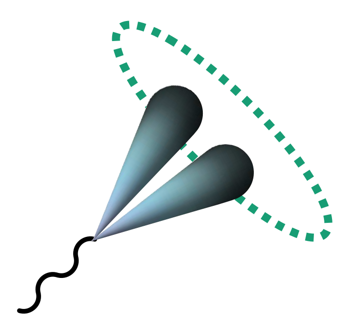
Jet Substructure Discrimination

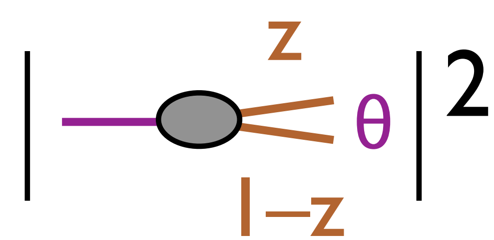


[Gavin Salam FCC talk, March 2015]



vs.



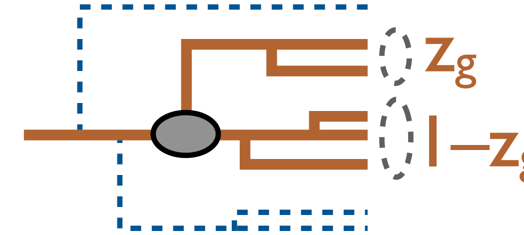


Splitting Function

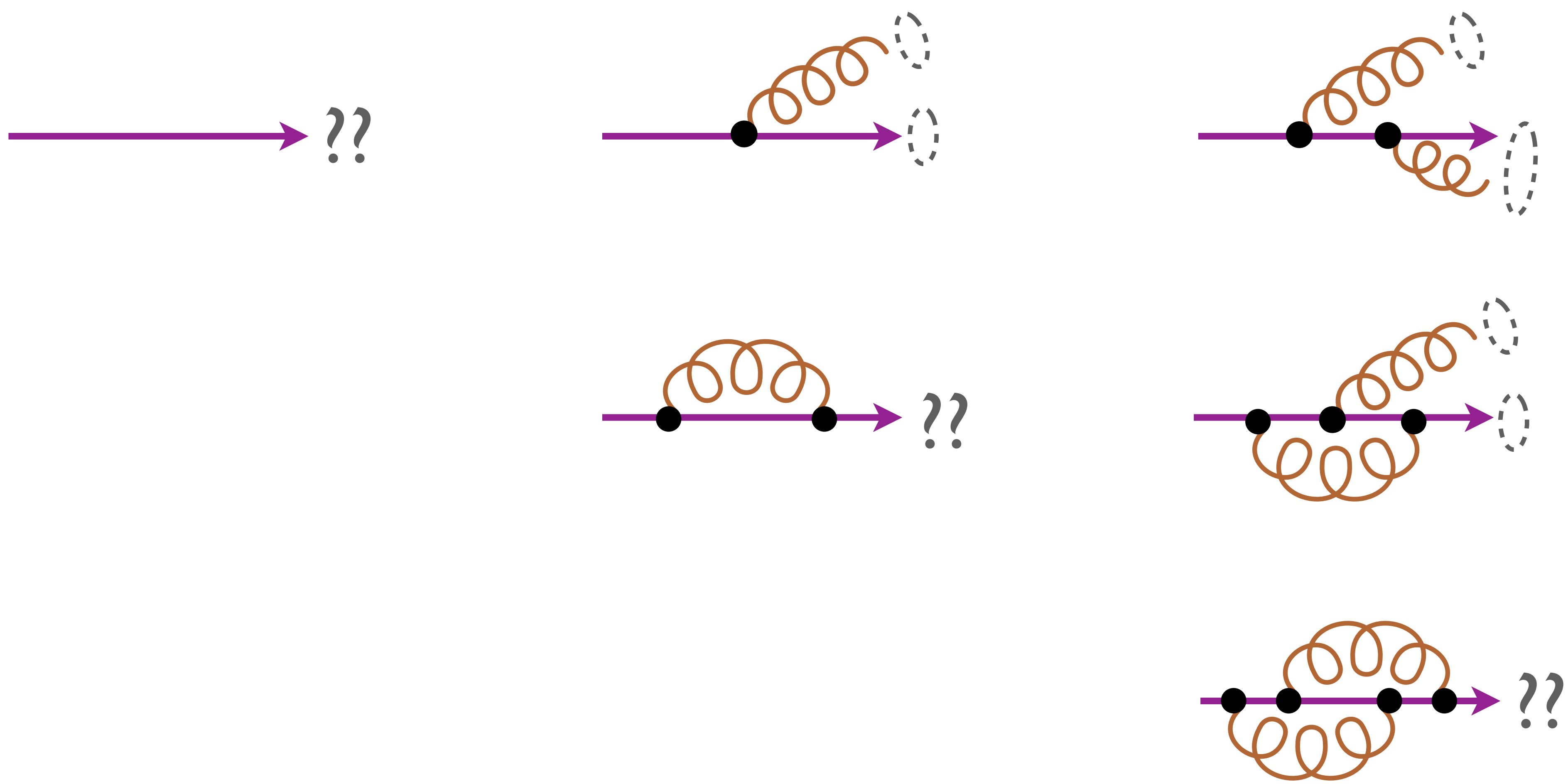
$1 \to 2$

$$\frac{2\alpha_s}{\pi} C_i \underbrace{\frac{\mathrm{d}\theta}{\theta}}_{\text{Collinear singularity}} \underbrace{\frac{\mathrm{d}z}{z}}_{\text{Soft singularity}}$$

Calculating Momentum Balance?



$$\frac{d\sigma}{dz_g} = \left(\textit{undefined} \right) + \alpha_s \left(\textit{infinity} \right) + \alpha_s^2 \left(\textit{infinity}^2 \right) + \dots$$



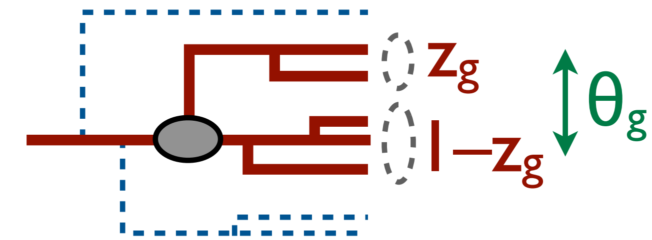
$\boxed{z_g}$

Collinear Unsafe*

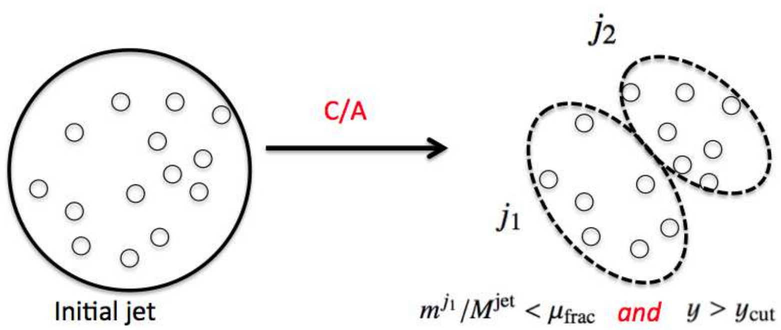
Can't make prediction from perturbative QCD (?)

*unless you simultaneously restrict jet mass

Calculating Groomed Jet Mass



Mass Drop



[Butterworth, Davison, Rubin, Salam, 0802.2470]

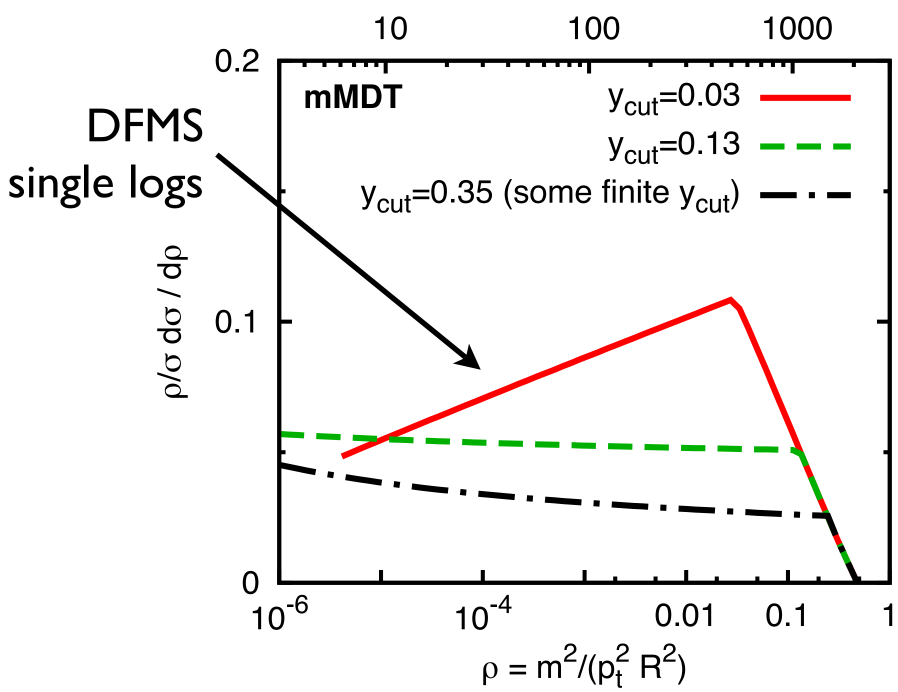
Soft Drop

$$z > z_{\rm cut}\,\theta^{\beta}$$

More Grooming | ≈ Mass Drop | Less Grooming

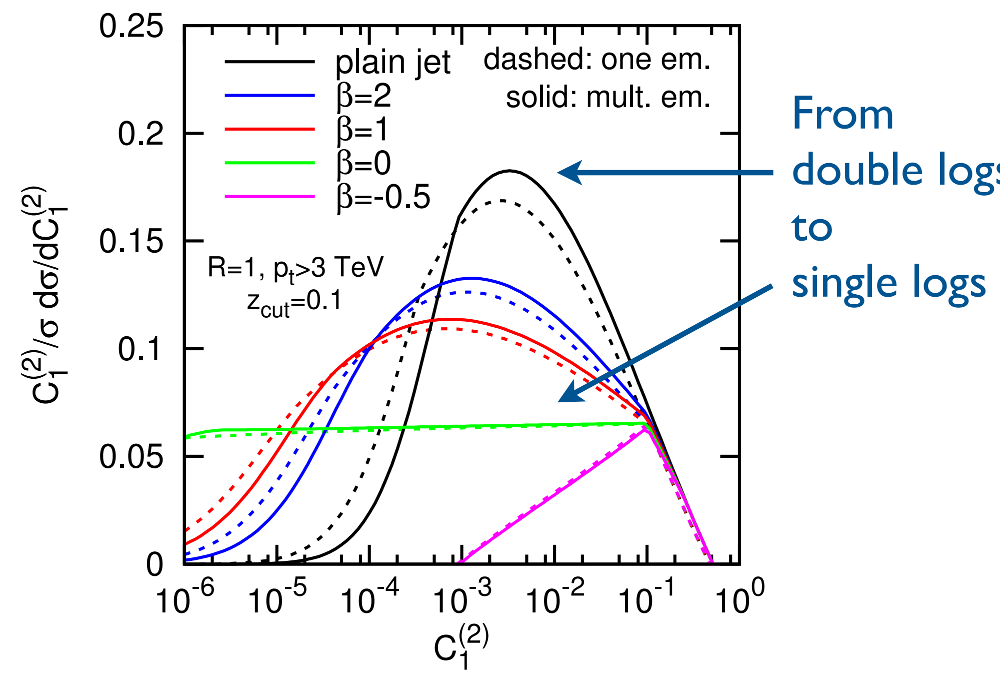
$\beta < 0$ | $\beta = 0$ | $\beta > 0$

Mass-Dropped Jet Mass



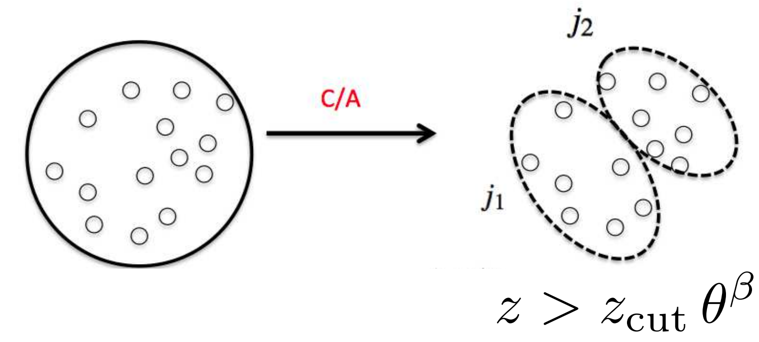
[Dasgupta, Fregoso, Marzani, Salam, 1307.0007]

Soft-Dropped Jet Mass

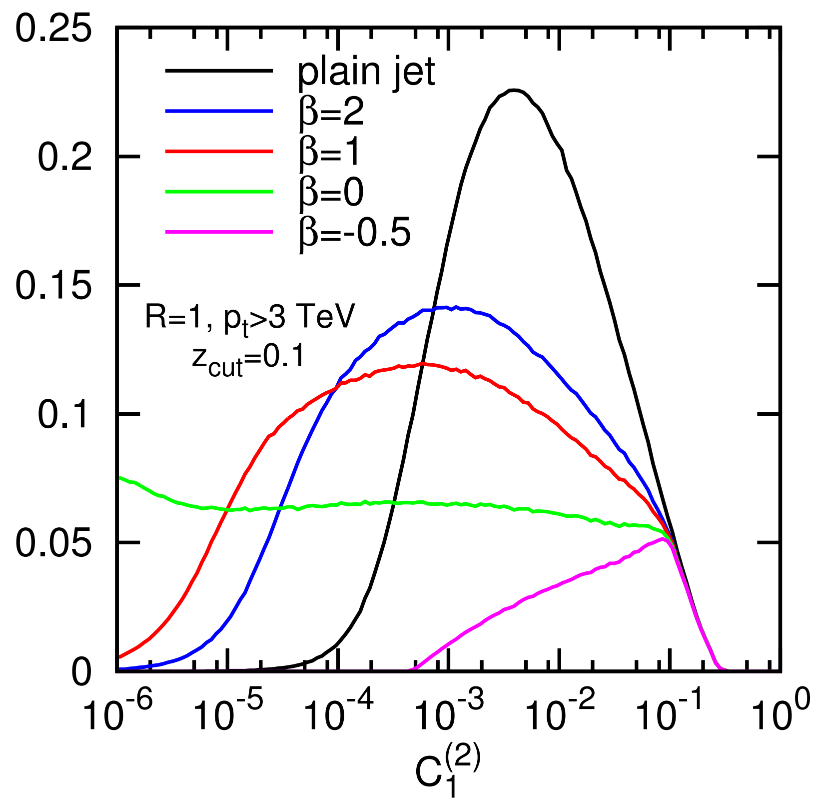


[Larkoski, Marzani, Soyez, JDT, 1402.2657]

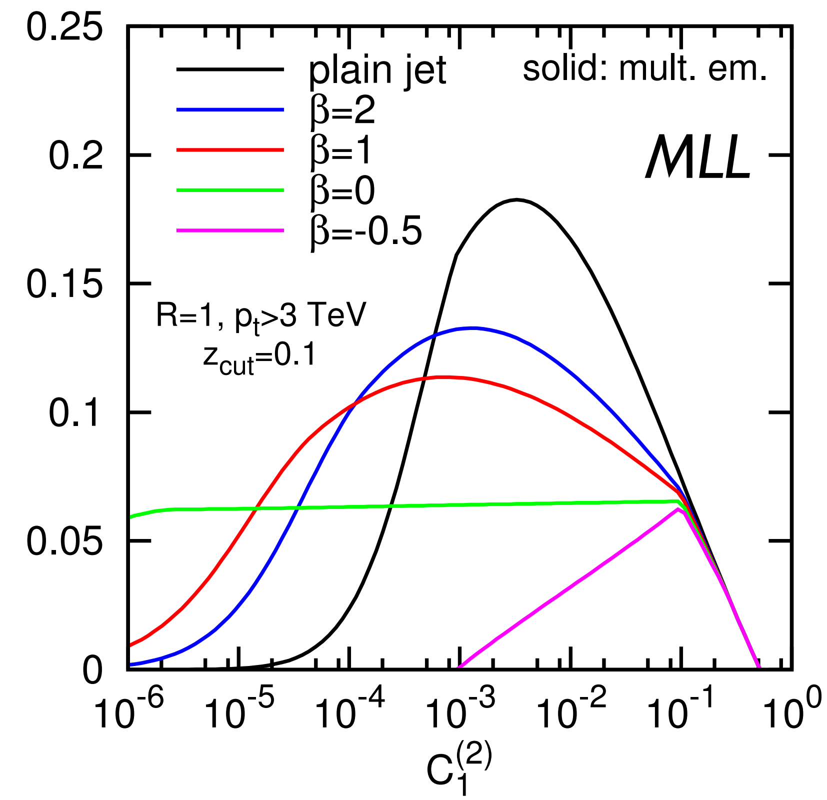
Soft-Dropped Jet Mass



Simulated LHC Data



First-principles QCD



More Grooming

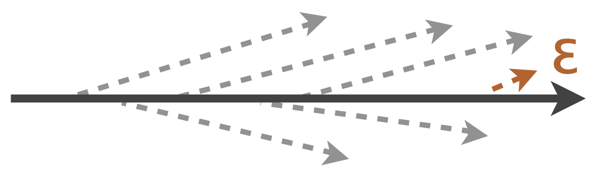
Less Grooming

$\beta \to -\infty$ $\beta < 0$ $\beta = 0$ $\beta > 0$ $\beta \to \infty$

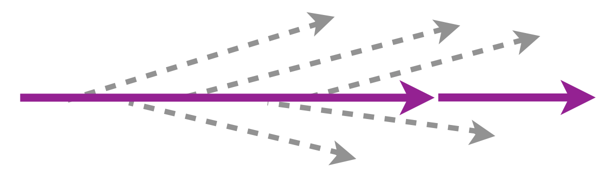
[Larkoski, Marzani, Soyez, JDT, 1402.2657]

Small Tweak to the Textbooks?

Infrared



Collinear



IRC Safe: $$\frac{d\sigma}{d\mathcal{O}} = \sum_N \int d\Phi_N \, \frac{d\sigma}{d\Phi_N} \, \delta\left[\mathcal{O} - \hat{\mathcal{O}}(\Phi_N)\right]$$

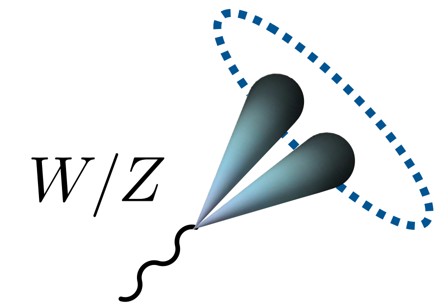
In IRC limit: $\hat{\mathcal{O}}(\Phi_{N-1})$

Also IRC Safe? $$\frac{d\sigma}{d\mathcal{O}} = \sum_N \int d\Phi_N \, \frac{d\sigma}{d\Phi_N} \, f(\mathcal{O}, \Phi_N)$$

Take IRC limit of $f(\mathcal{O}, \Phi_{N+1})$

More About R2 D_2

D_2: Test for 2-Prong Substructure



Energy correlation functions:

$$e_2^{(\beta)} = \sum_{i<j} z_i \, z_j \, (R_{ij})^\beta$$

$$e_3^{(\beta)} = \sum_{i<j<k} z_i \, z_j \, z_k \, (R_{ij} R_{jk} R_{ki})^\beta$$

momentum fraction
$z = p_T/p_{Tjet}$

pair-wise
angles

adjustable exponent
ATLAS: $\beta=1$

[Larkoski, Salam, JDT, 1305.0007; see also Banfi, Salam, Zanderighi, hep-ph/0407286; Jankowiak, Larkoski, 1104.1646]

Discriminants:

$X_2 \to 0$ for exactly 2-prong

$$C_2 = \frac{e_3}{(e_2)^2}$$

Natural choice?

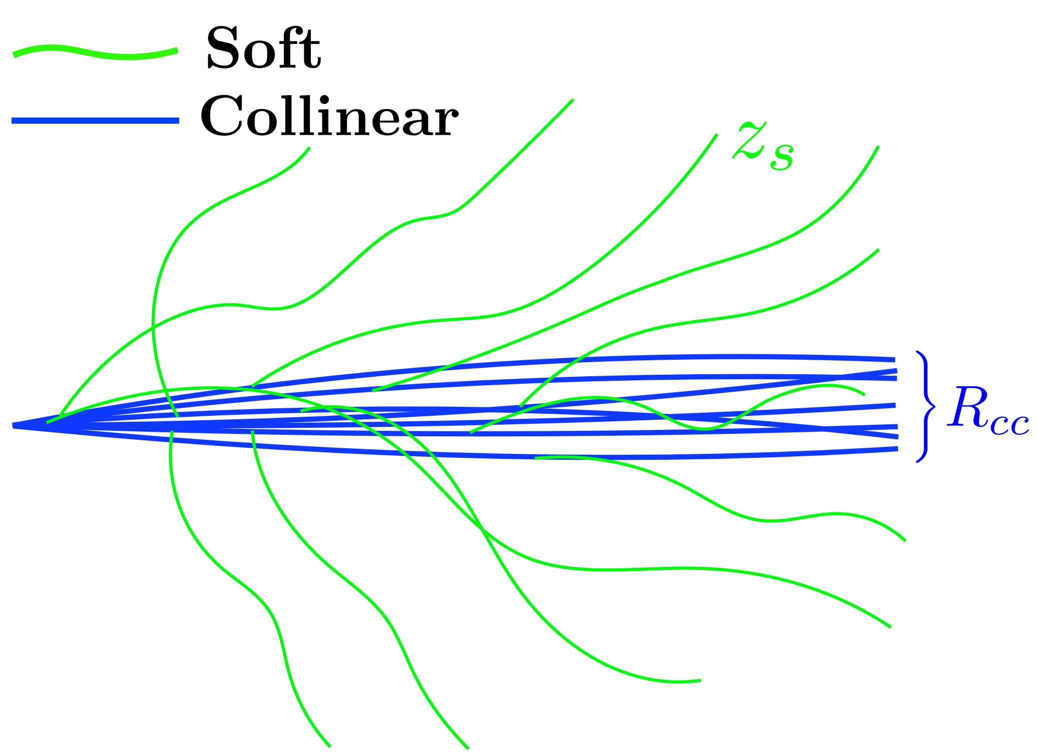
$$D_2 = \frac{e_3}{(e_2)^3}$$

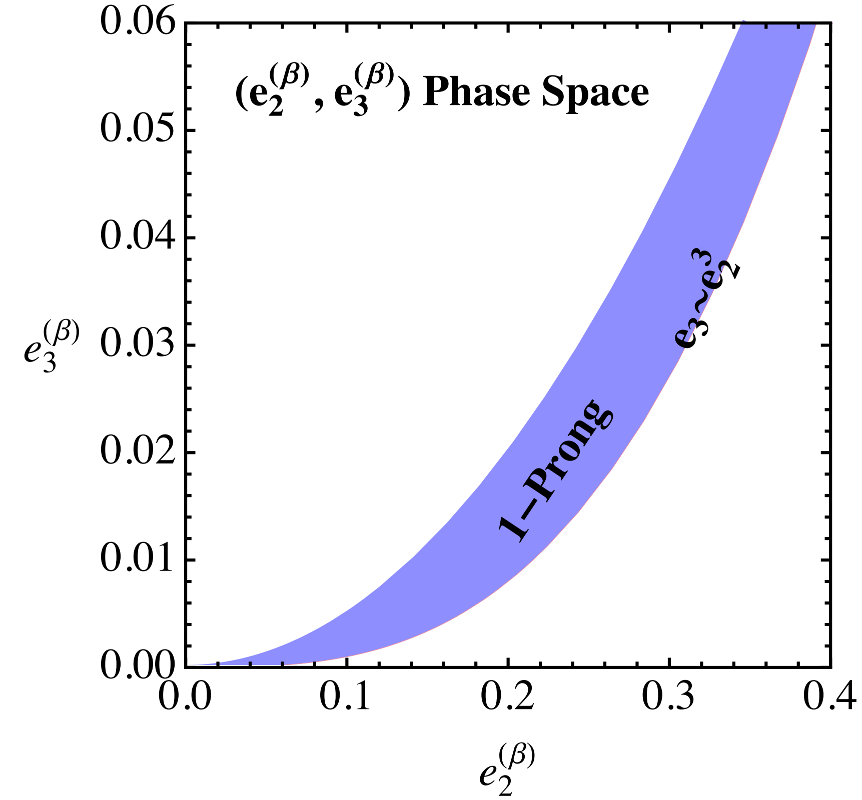
key!

Provably best choice!

[Larkoski, Moult, Neill, 1409.6298]

Power Counting: 1-prong Background





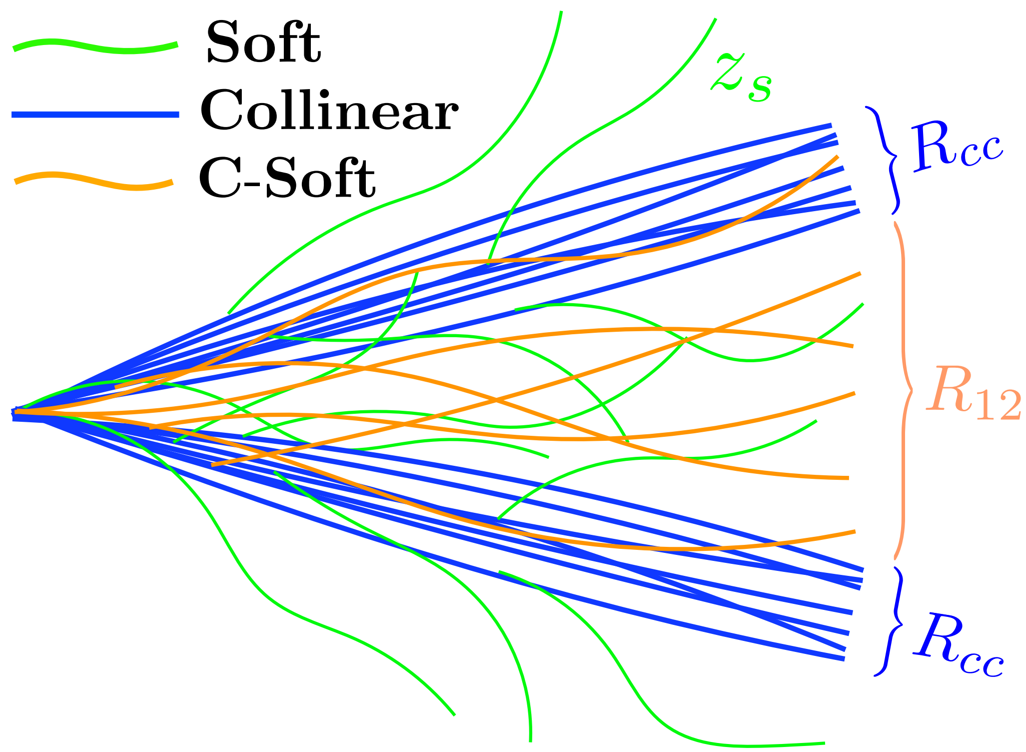
	C	S
$z_i \simeq$	1	z_s
	CC	SX
$R_{ij} \simeq$	R_{cc}	1

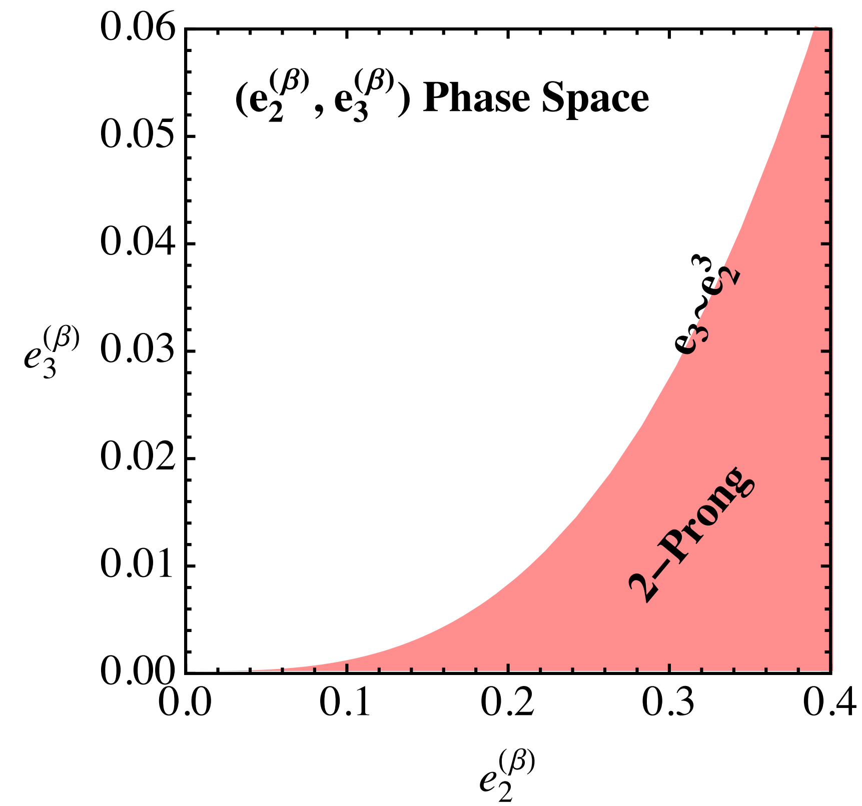
$$e_2 \simeq \underset{\text{CC}}{R_{cc}} + \underset{\text{CS}}{z_s}$$

$$e_3 \simeq \underset{\text{CCC}}{R_{cc}^3} + \underset{\text{CCS}}{R_{cc} z_s} + \underset{\text{CSS}}{z_s^2}$$

[Larkoski, Moult, Neill, 1409.6298, 1507.03018]

Power Counting: 2-prong Signal





C | Cs | S

$$z_i \simeq \quad 1 \qquad z_{cs} \qquad z_s$$

CC | C1C2 or CCs | SX

$$R_{ij} \simeq \quad R_{cc} \qquad R_{12} \qquad 1$$

C1C2

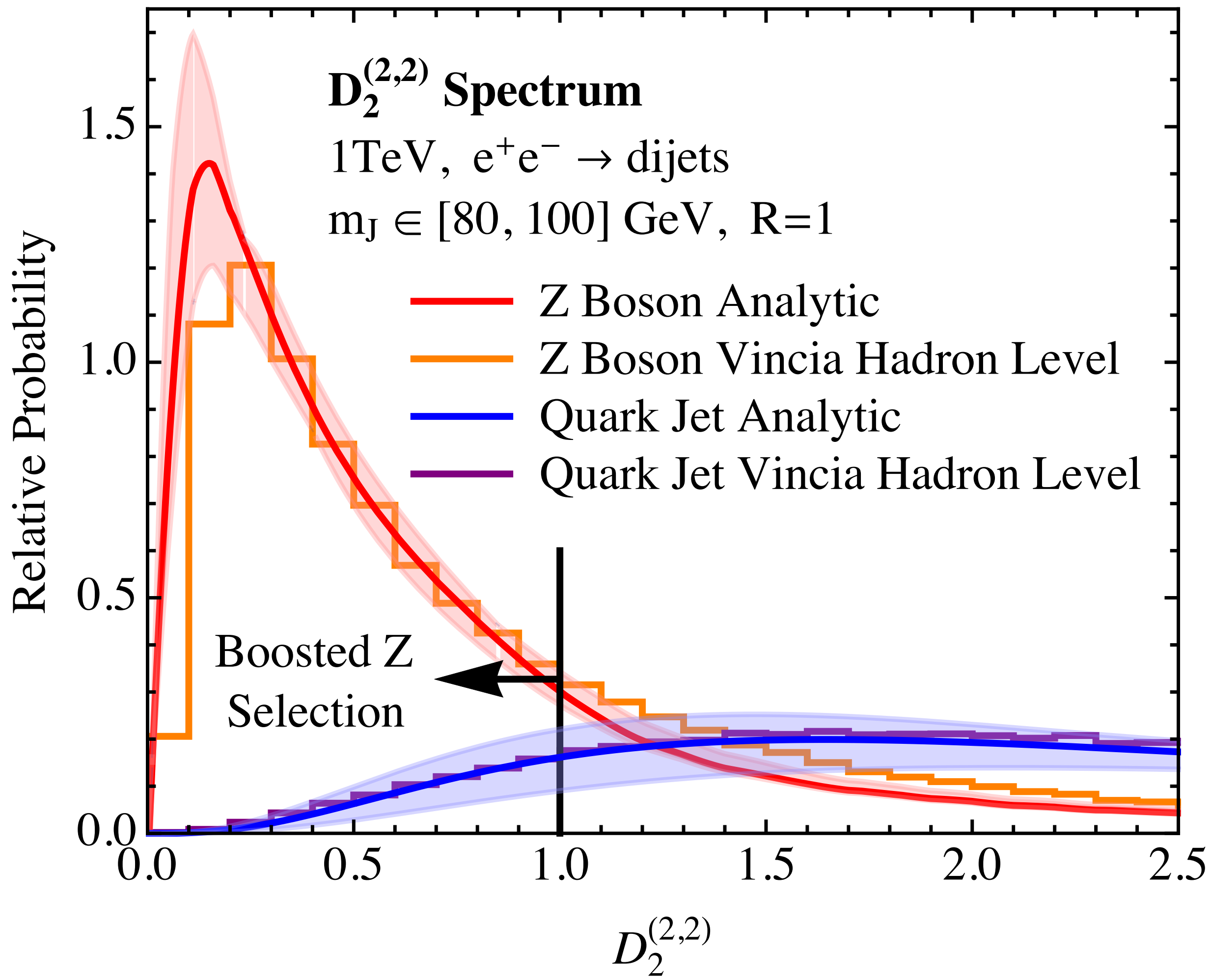
$$e_2 \simeq R_{12}$$

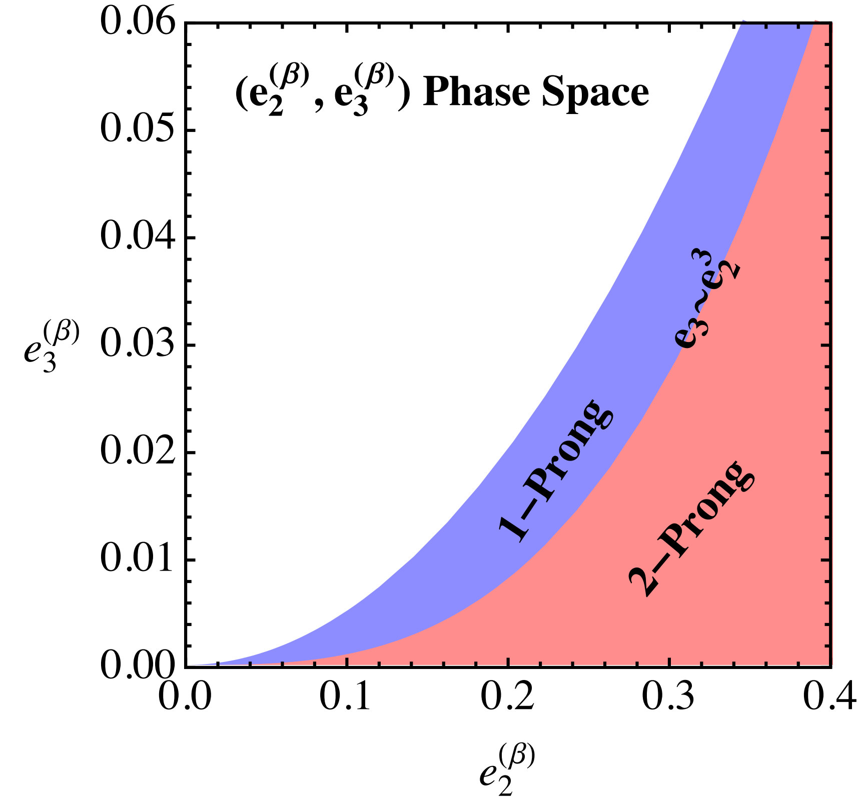
C1C2S | C1C2C | C1C2Cs

$$e_3 \simeq R_{12} z_s + R_{12}^2 R_{cc} + R_{12}^3 z_{cs}$$

[Larkoski, Moult, Neill, 1409.6298, 1507.03018; collinear-soft modes and soft-collinear modes also appear in Bauer, Tackmann, Walsh, Zuberi, 1106.6047; Procura, Waalewijn, Zeune, 1410.6483; Larkoski, Moult, Neill, 1501.04596; Chien, Hornig, Lee, 1509.04287; Pietrulewicz, Tackmann, Waalewijn, 1601.05088; see also coft modes in Becher, Neubert, Rothen, Shao, 1508.06645, 1605.02737]

Optimal 2-prong Discriminant: $D_2 = \frac{e_3}{(e_2)^3}$





Novel QCD calculation based on
merging two SCET factorization theorems (!)
and projecting triple-differential cross section (!)

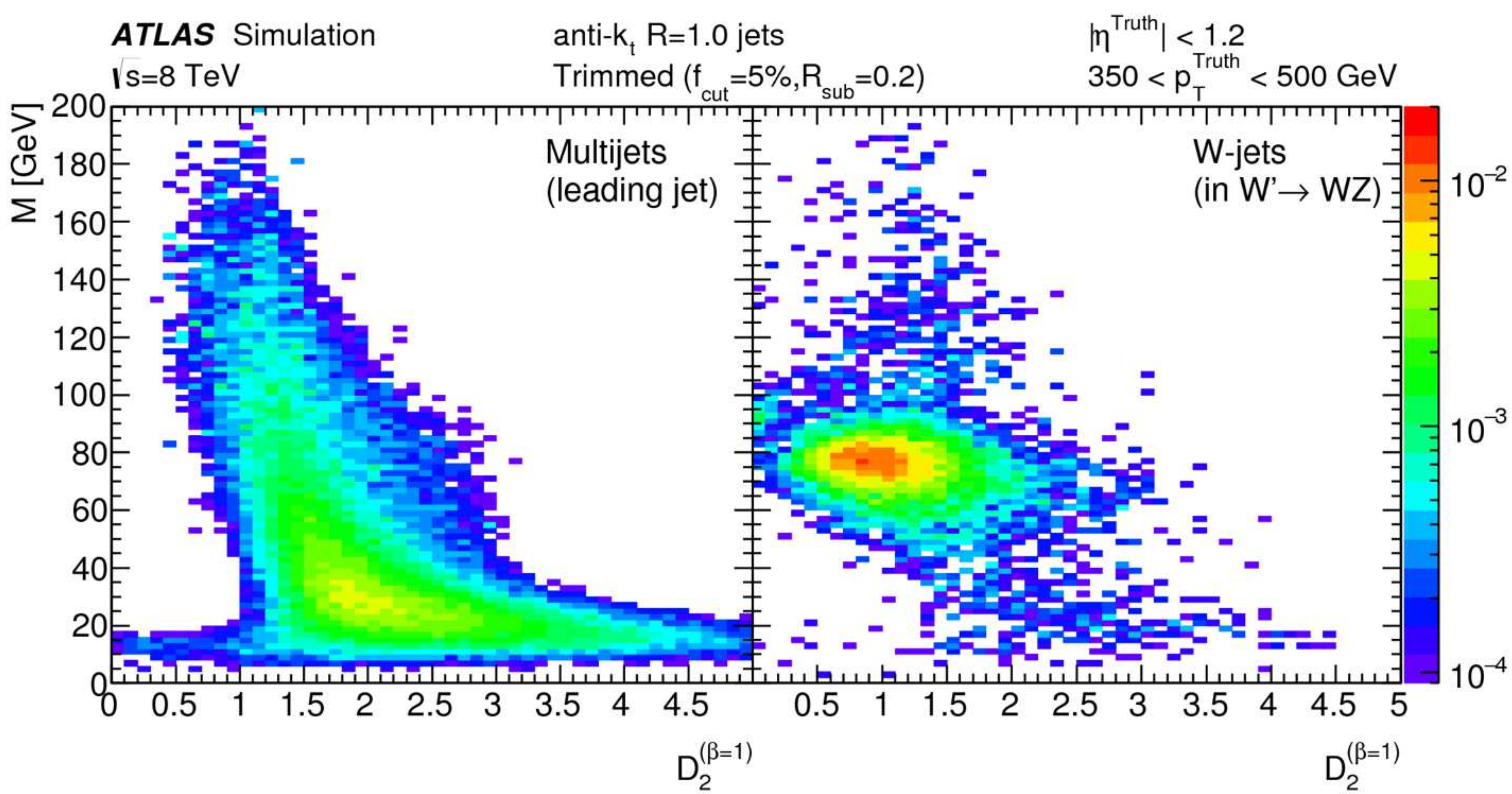
(n.b. e^+e^- calculation with $\beta = 2$)

Unlike C_2, clean separation of 1-prong from 2-prong

Basis for ATLAS "R2 D_2" tagger

[Larkoski, Moult, Neill, 1409.6298,1507.03018]

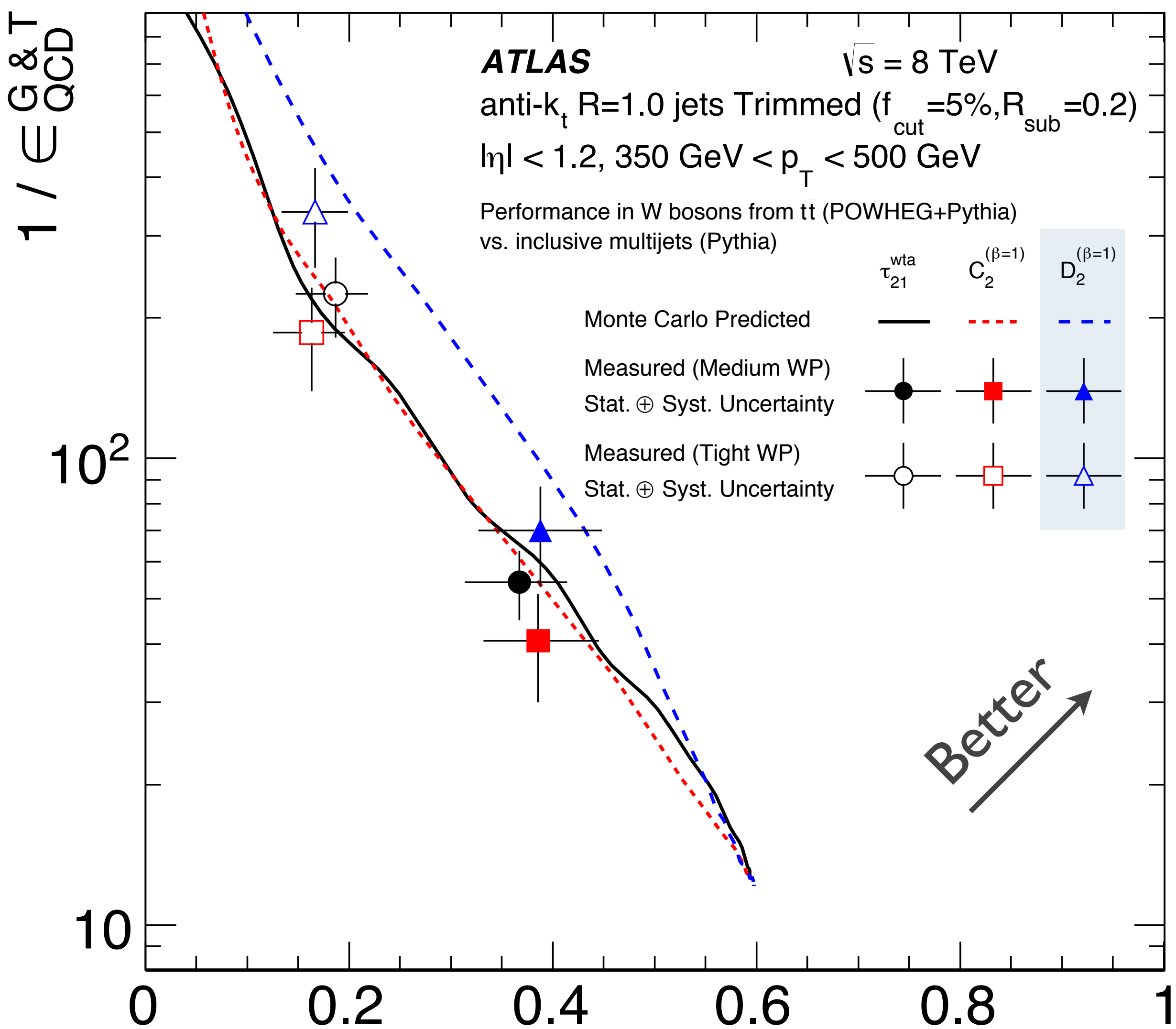
ATLAS 13 TeV Baseline: "R2 D_2"



R_{sub} = 0.2 trimming with D_2 tagging

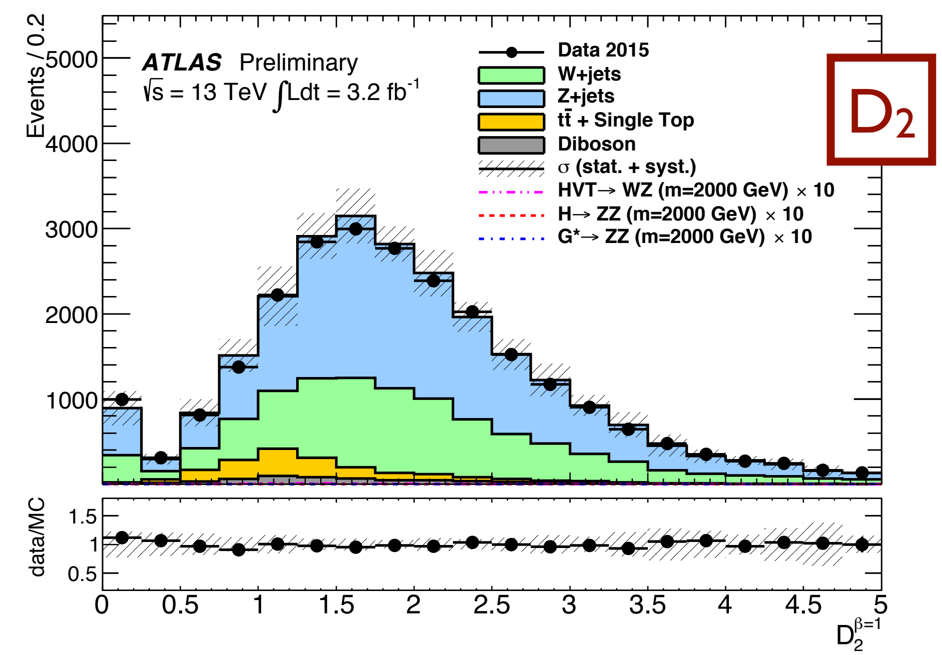
[ATLAS, 1510.05821]

ATLAS 13 TeV Baseline: “R2 D_2”



[ATLAS, 1510.05821]

First 13 TeV results



[ATLAS-CONF-2015-068, -071, -075, -080]

More About Quarks vs. Gluons

Quarks vs. Gluons on One Slide

Cartoon:

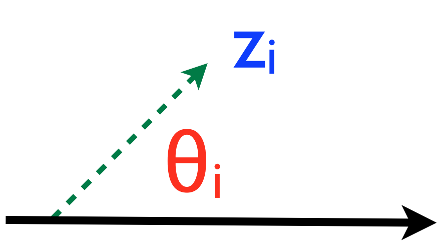
Quark: C_F = 4/3 vs. Gluon: C_A = 3

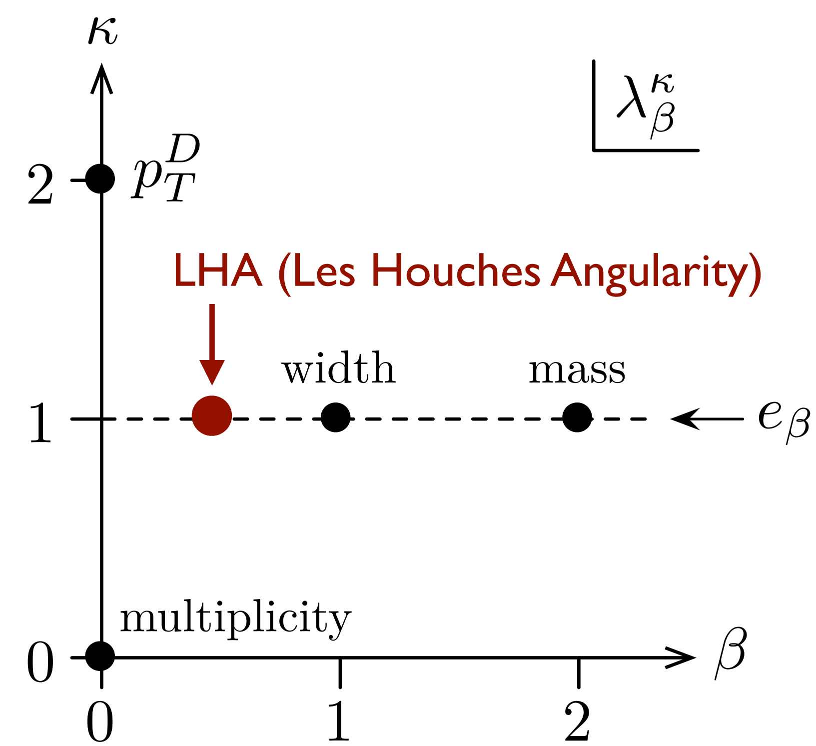
Probe radiation pattern with e.g. Generalized Angularities

$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \theta_i^\beta$$

momentum fraction

angle to recoil-free axis





[Larkoski, JDT, Waalewijn, 1408.3122]
[based on Berger, Kucs, Sterman, hep-ph/0303051; Ellis, Vermilion, Walsh, Hornig, Lee, 1001.0014]
[see also Larkoski, Salam, JDT, 1305.0007; Larkoski, Neill, JDT, 1401.2158]
[For a more complete catalog, see Gallicchio, Schwartz, 1106.3076, 1211.7038]

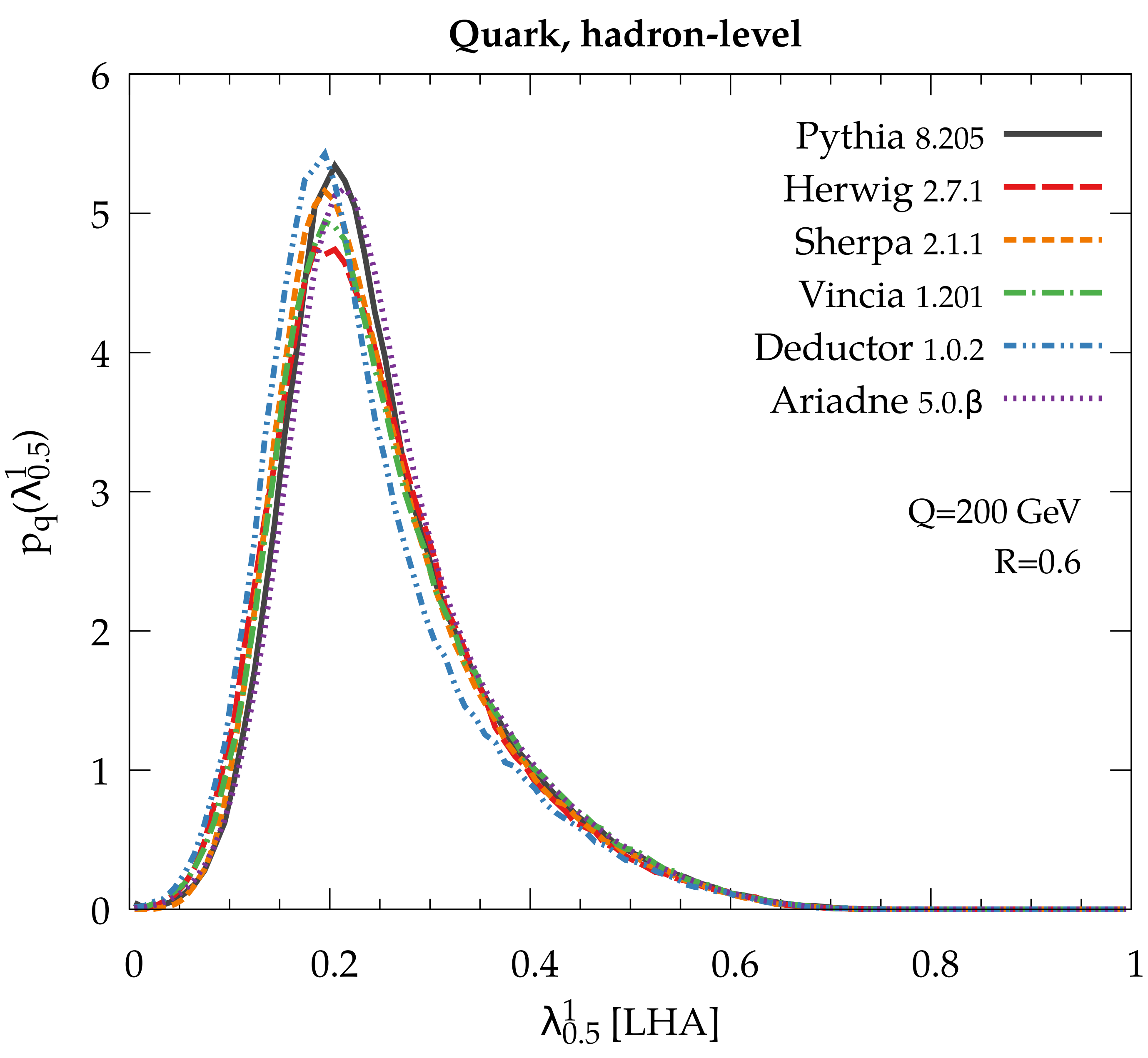
What is a Quark Jet?

From lunch/dinner discussions

Ill-Defined	What people sometimes think we mean	
	Quark as noun	A quark parton
		A Born-level quark parton
		The initiating quark parton in a final state shower
		An eikonal line with baryon number 1/3 and carrying triplet color charge
		A quark operator appearing in a hard matrix element in the context of a factorization theorem
		A parton-level jet object that has been quark-tagged using a soft-safe flavored jet algorithm (automatically collinear safe if you sum constituent flavors)
	Quark as adjective	A phase space region (as defined by an unambiguous hadronic fiducial cross section measurement) that yields an enriched sample of quarks (as interpreted by some suitable, though fundamentally ambiguous, criterion)
Well-Defined	What we mean	

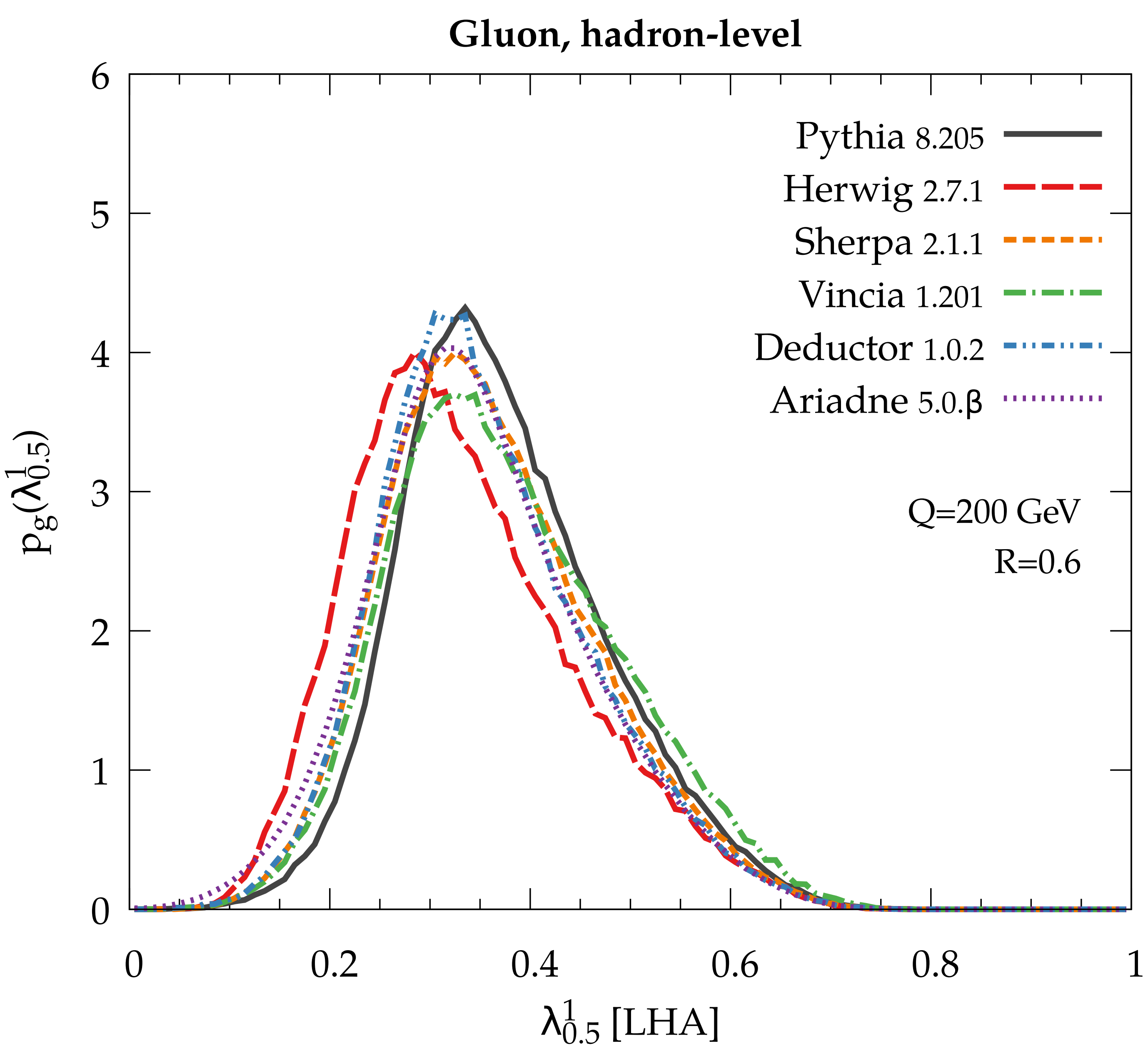
Les Houches Angularity: Quarks

Hadron level, R=0.6, e^+e^- @ Q=200 GeV



Les Houches Angularity: Gluons

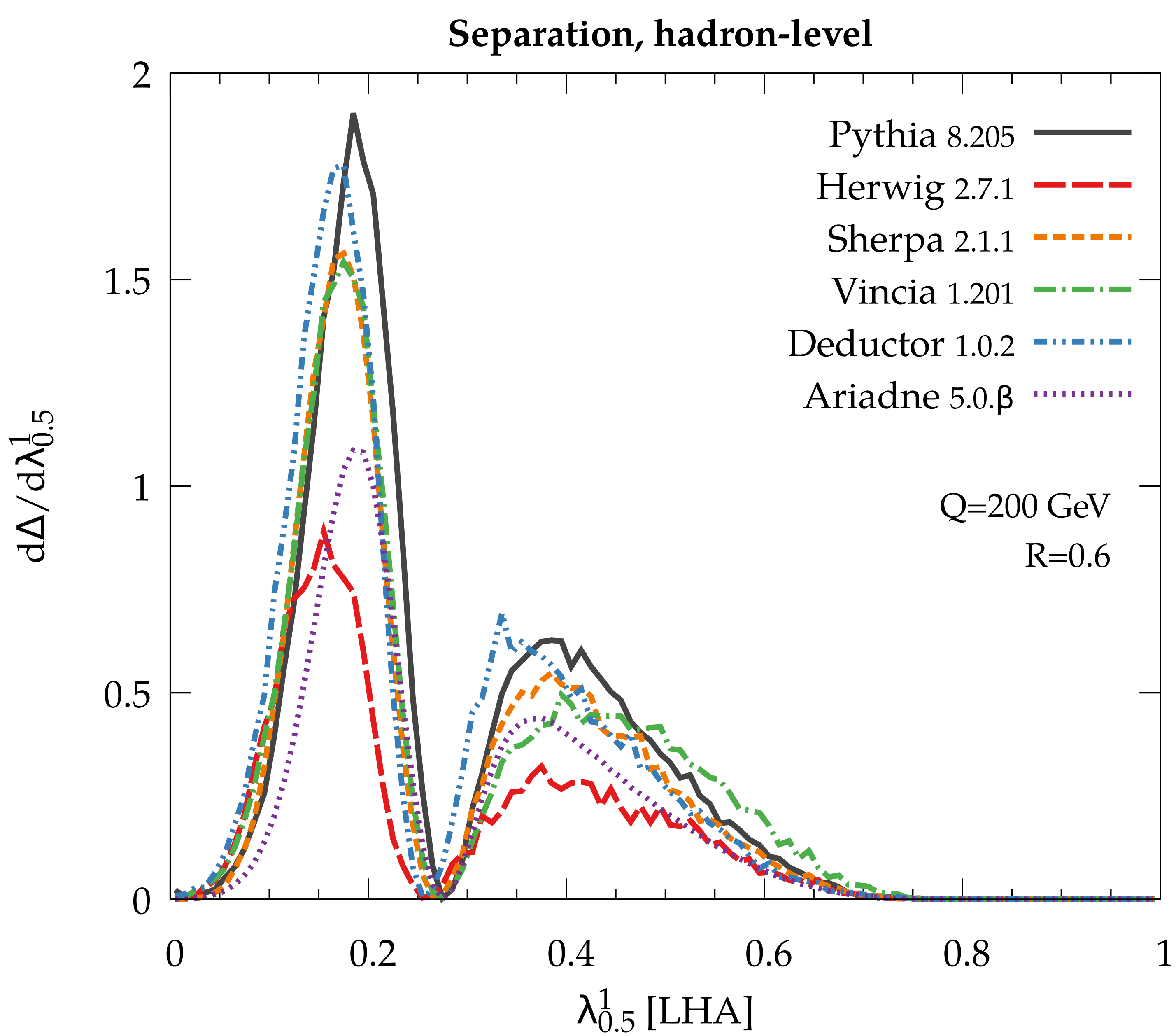
Hadron level, R=0.6, e^+e^- @ Q=200 GeV



LHA: Quark/Gluon Separation

Hadron level, R=0.6, e^+e^- @ Q=200 GeV

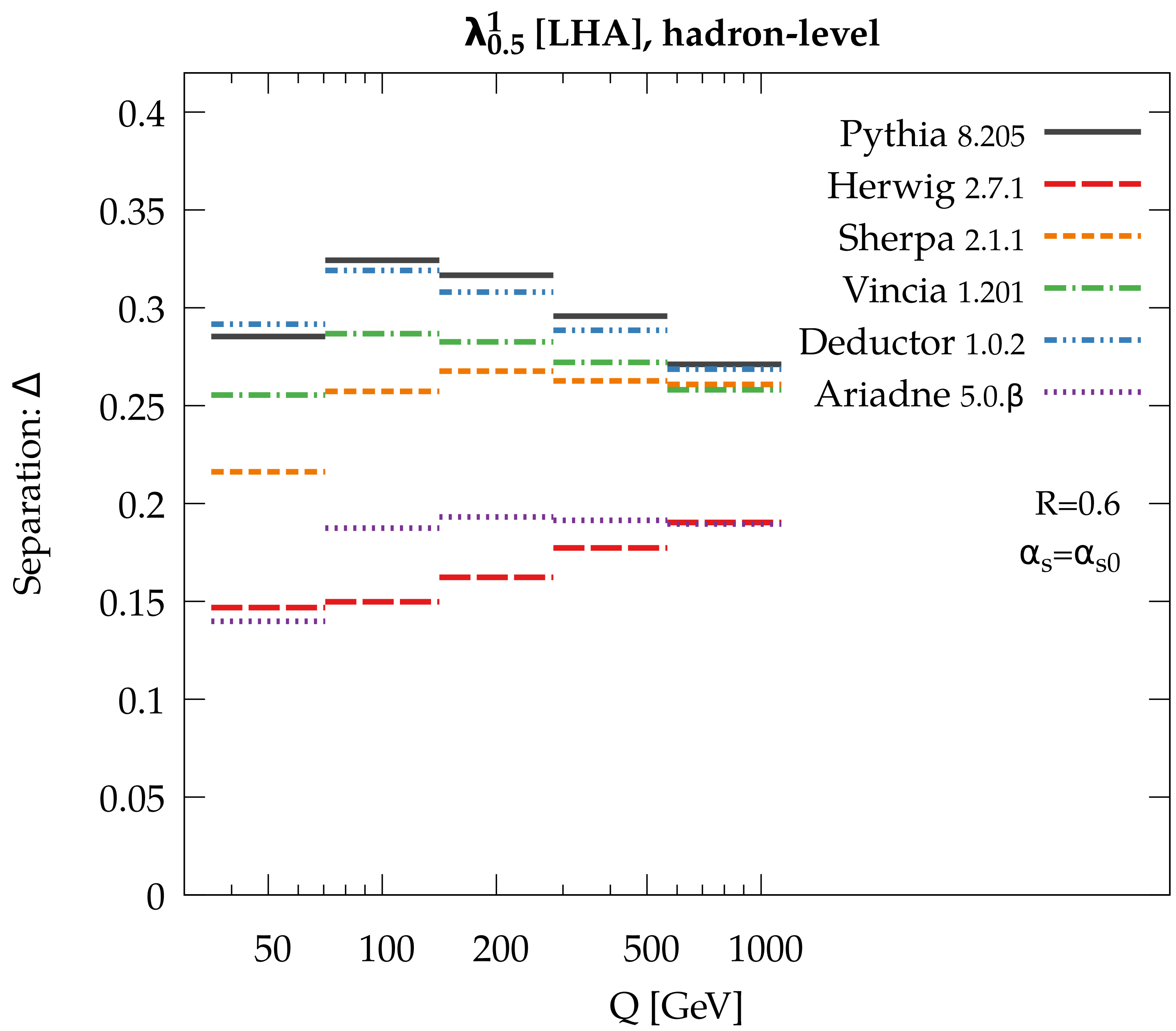
$$\frac{(S(\lambda) - B(\lambda))^2}{2(S(\lambda) + B(\lambda))}$$



Total Separation Power

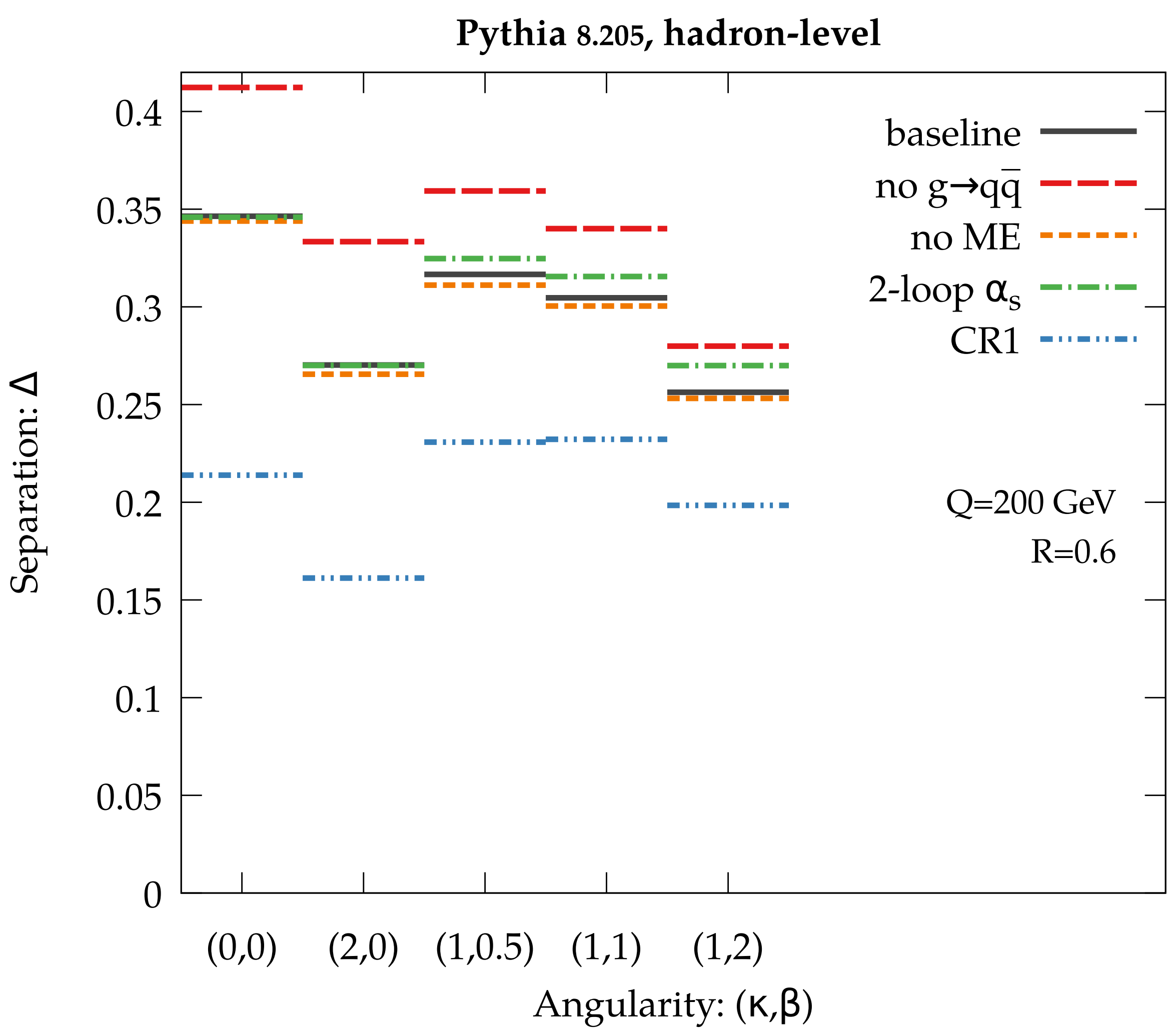
Hadron level, R=0.6, e^+e^-

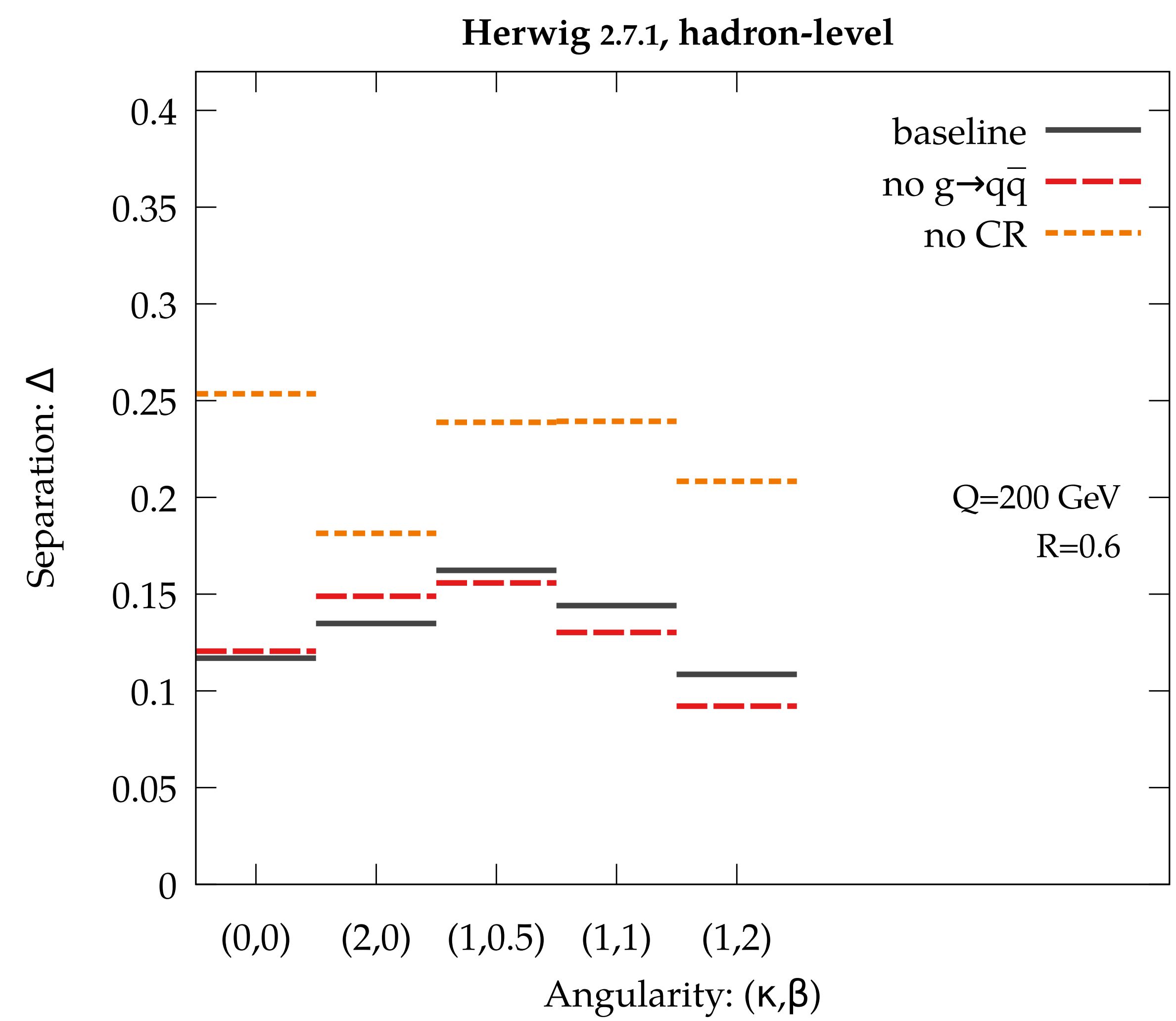
$$\int d\lambda \, \frac{\left(S(\lambda) - B(\lambda)\right)^2}{2(S(\lambda) + B(\lambda))}$$



Opportunities for Analytics/Tuning

Hadron level, R=0.6, e^+e^- @ Q=200 GeV

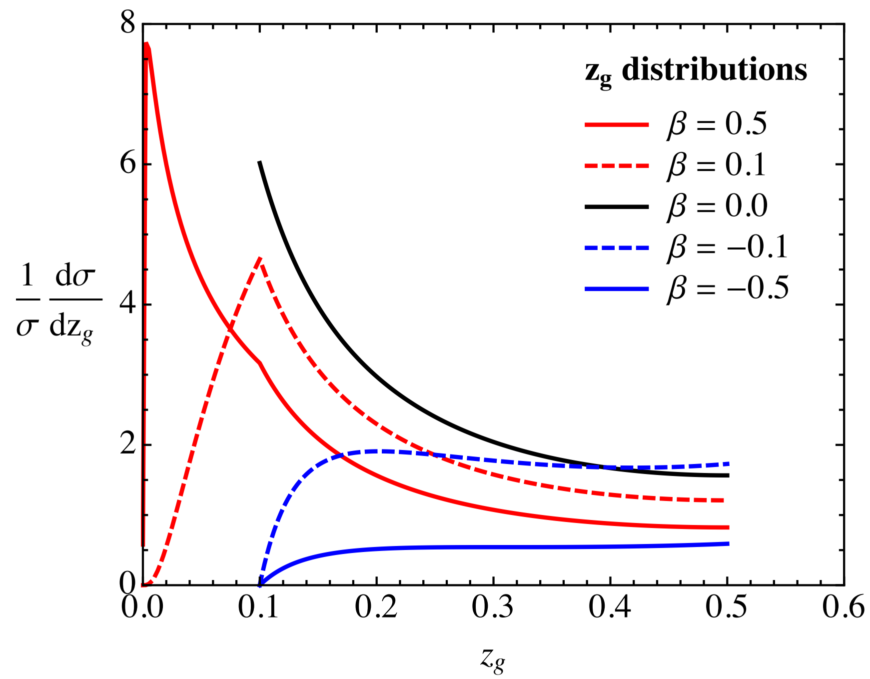


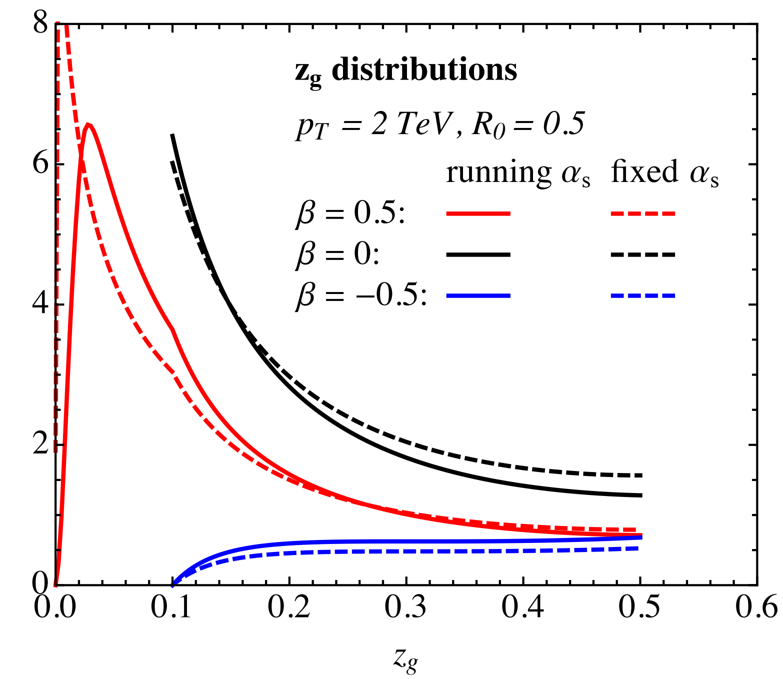


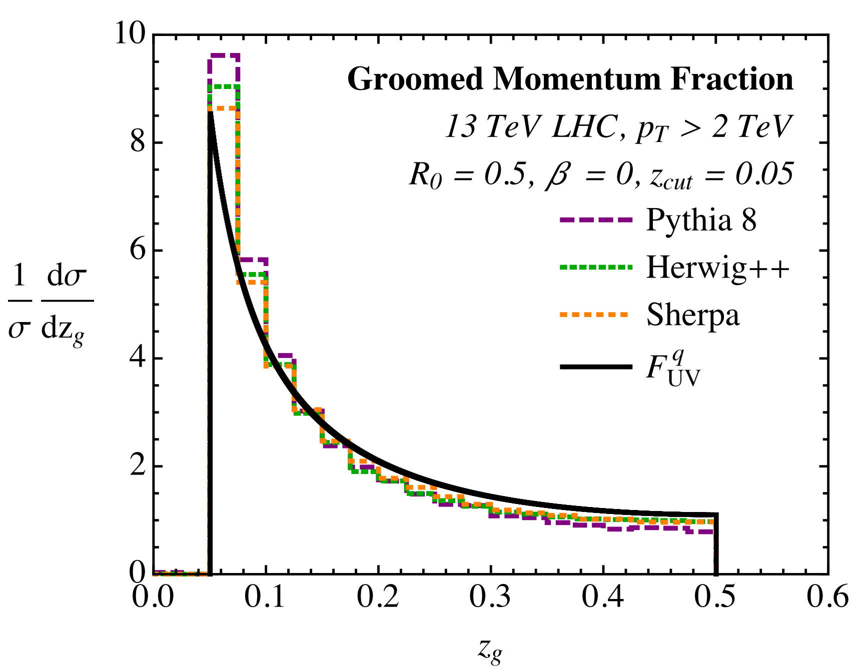
Puzzling trends require deeper study

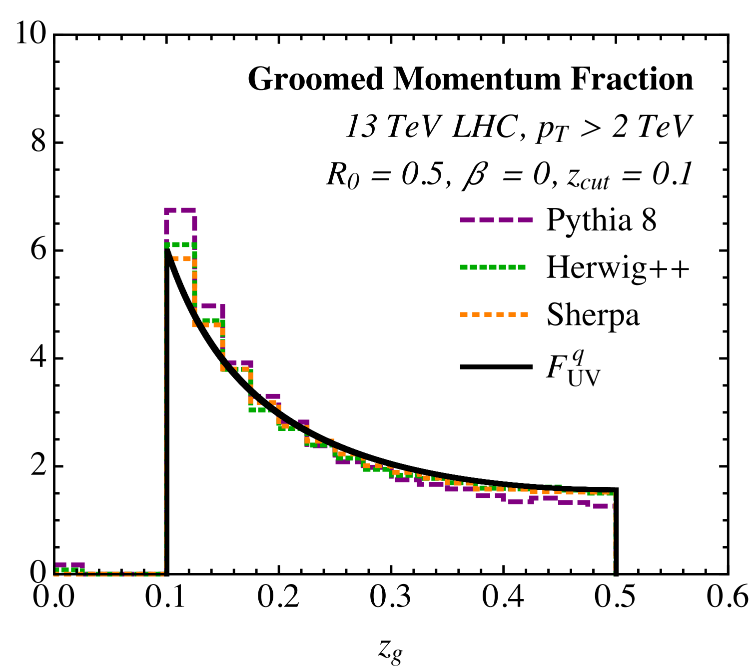
More About Open Data

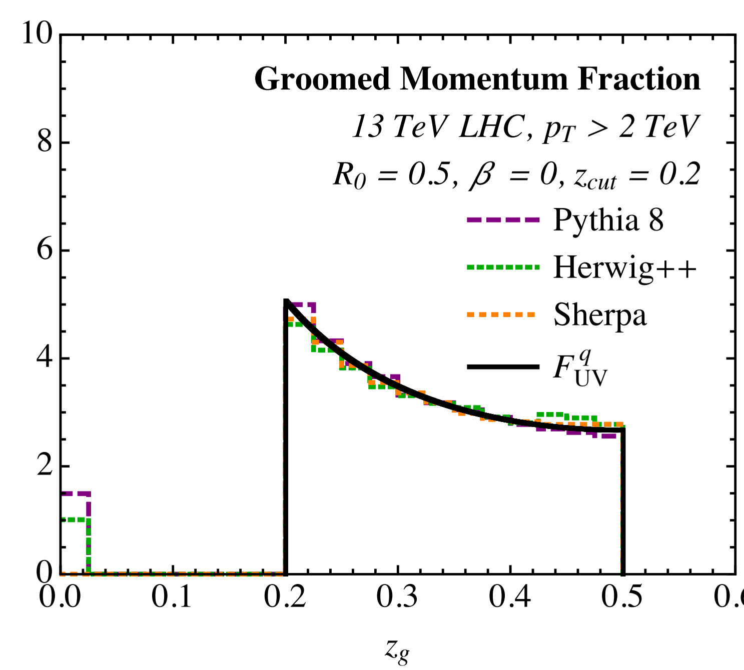
Additional z_g Theory Plots





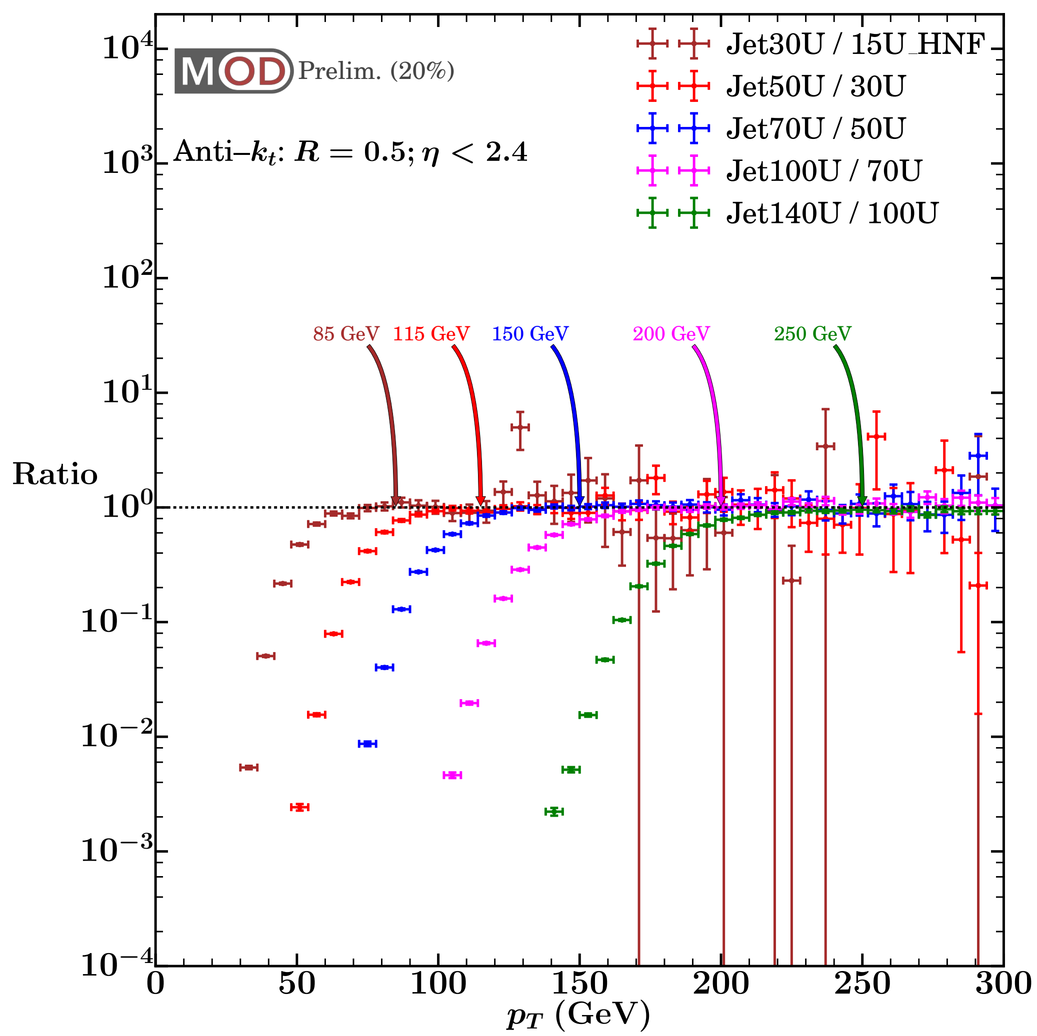


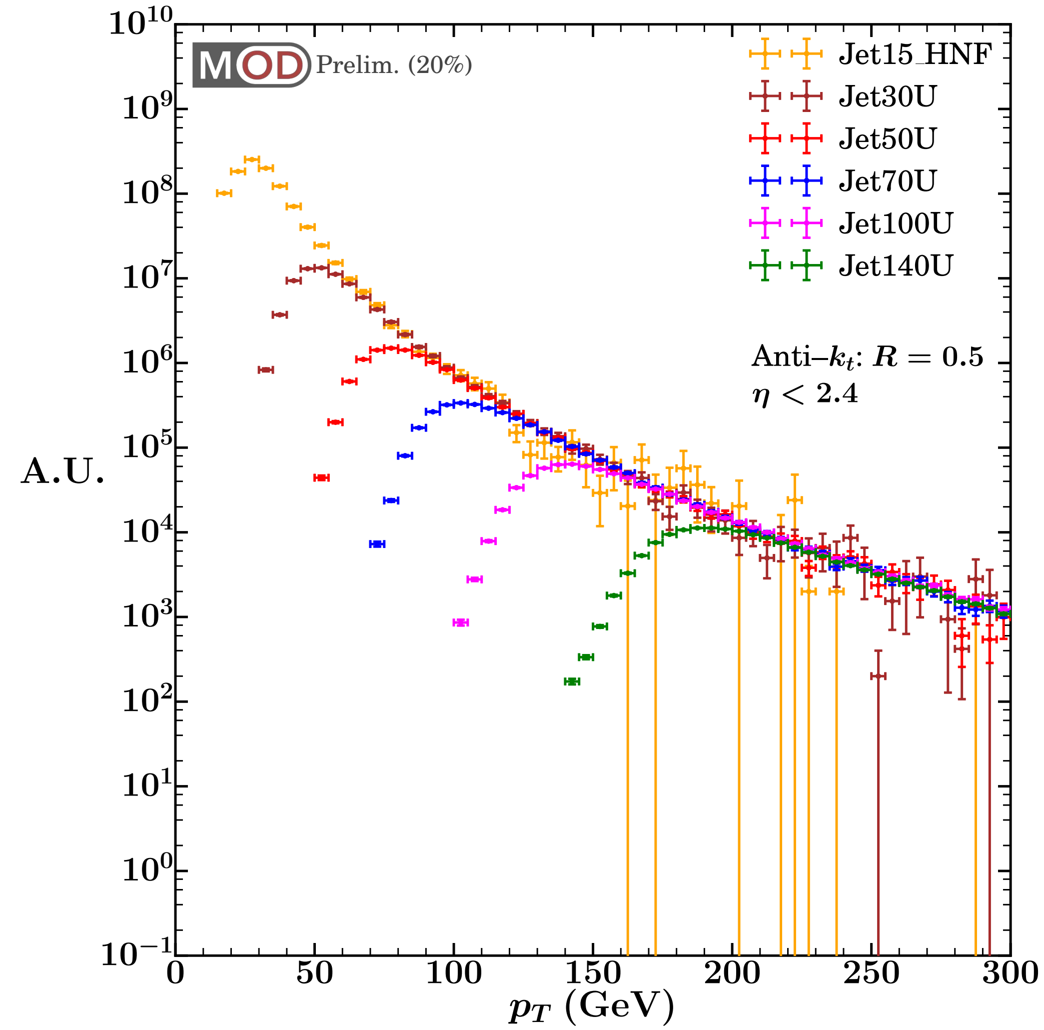




[Larkoski, Marzani, JDT, 1502.01719]

CMS Jet Primary Data Set Triggers





HLT_Jet15U + _v3
HLT_Jet15U_HcalNoiseFiltered + _v3
HLT_Jet30U + _v3
HLT_Jet50U + _v3
HLT_Jet70U + _v2 + _v3
HLT_Jet100U + _v2 + _v3
HLT_Jet140U_v1 + _v3
HLT_Jet180U_v3

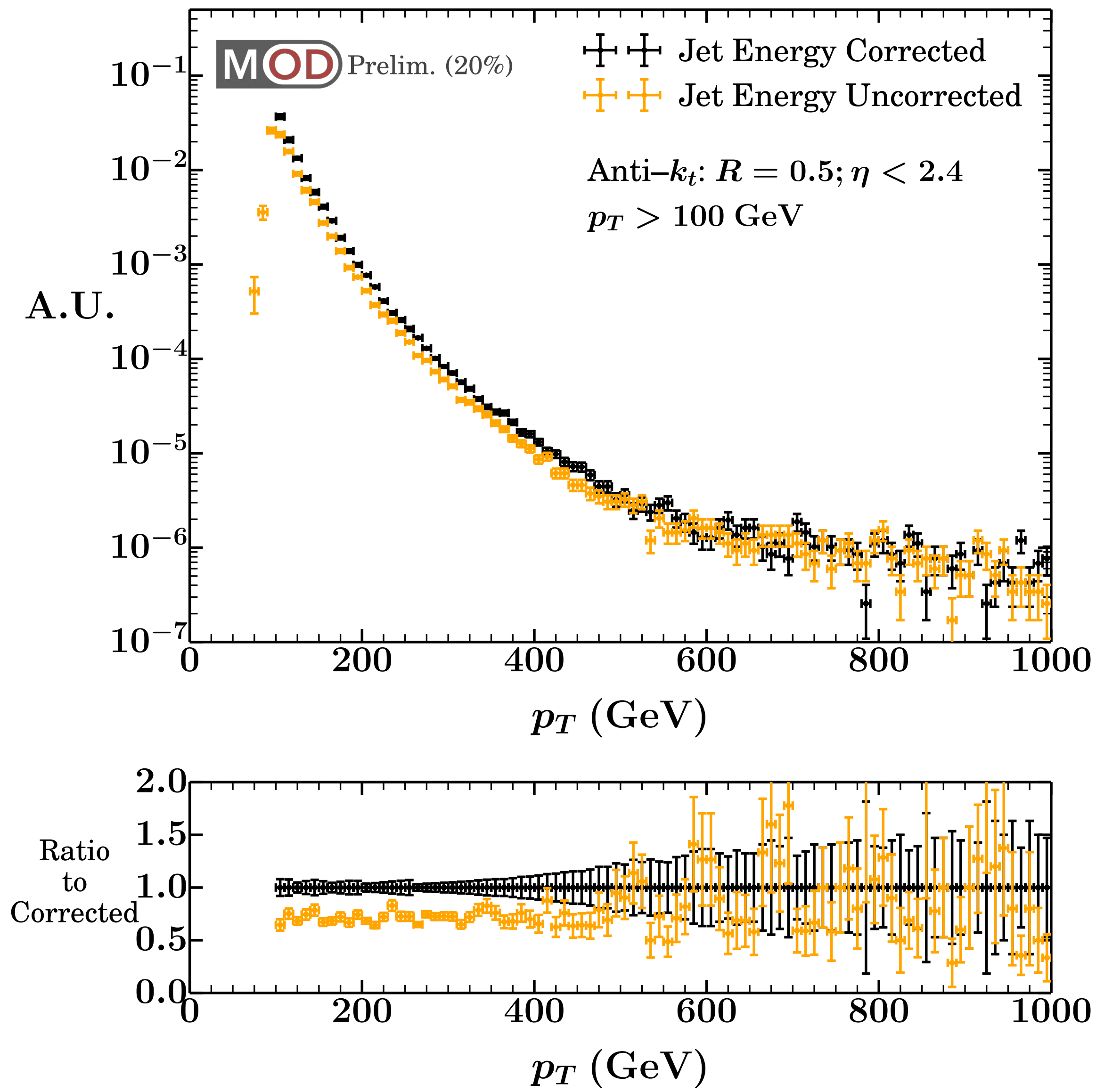
HLT_DiJetAve15U + _v3
HLT_DiJetAve30U + _v3
HLT_DiJetAve50U + _v3
HLT_DiJetAve70U + _v2 + _v3
HLT_DiJetAve100U_v1 + _v3
HLT_DiJetAve140U_v3

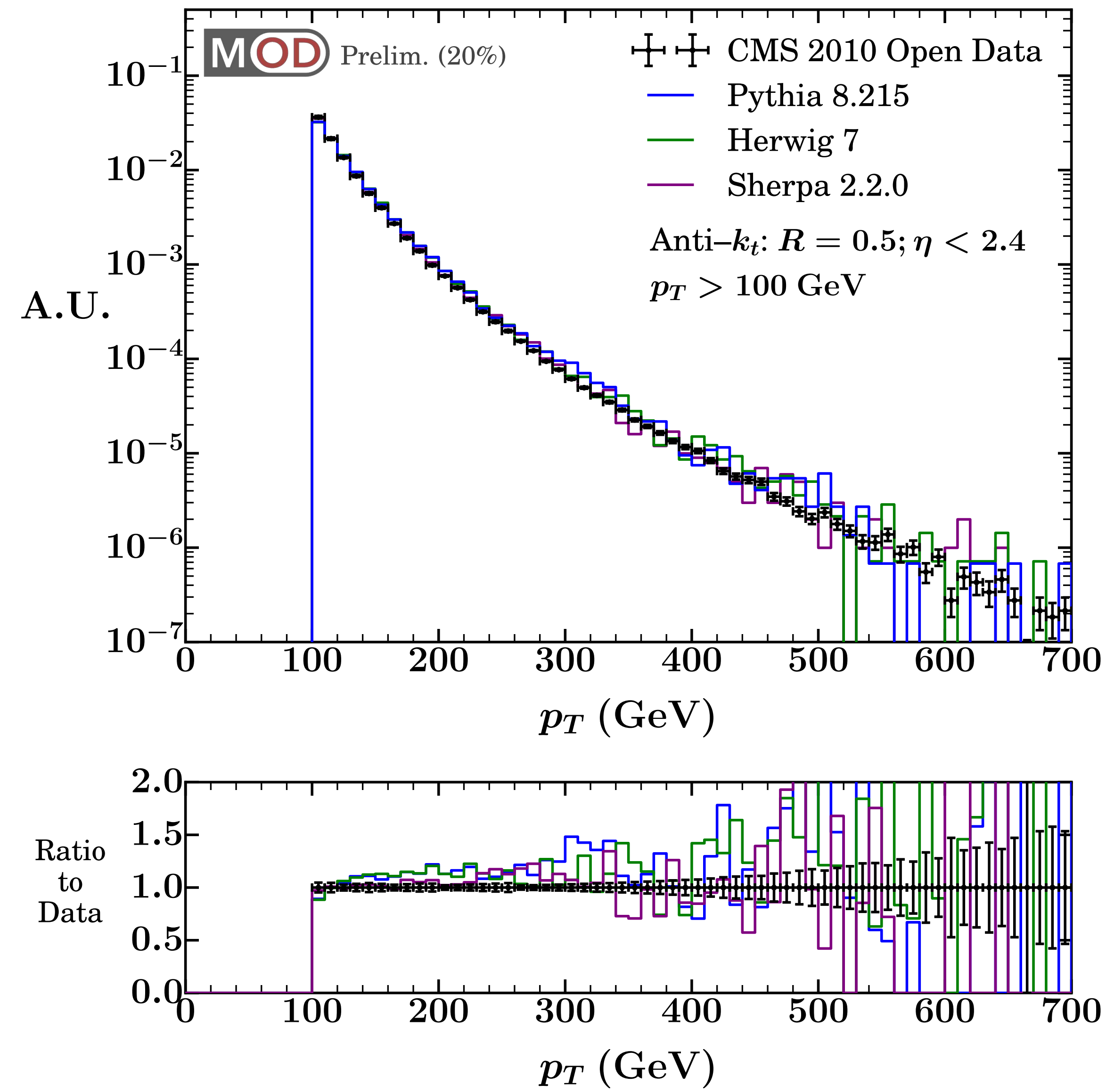
HLT_QuadJet20U
HLT_QuadJet25U

HLT_HT100U
HLT_HT120U
HLT_HT140U

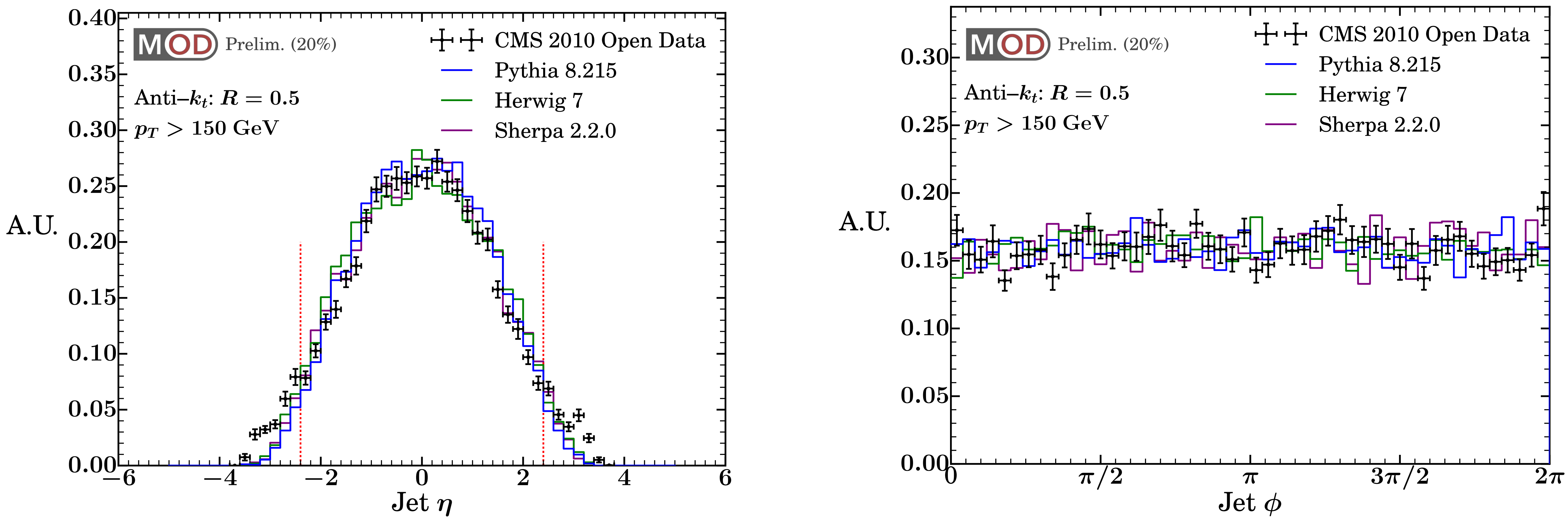
HLT_EcalOnly_SumEt160

Corrected Jet p_T Spectrum

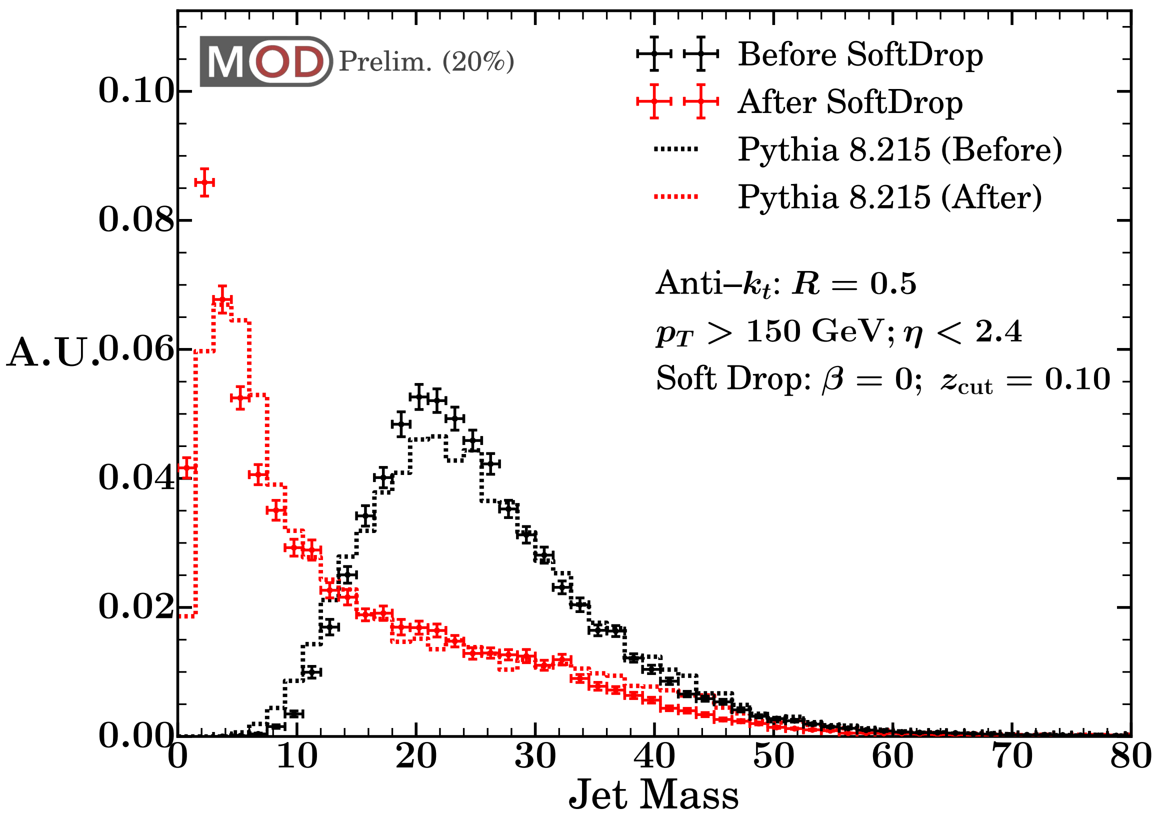


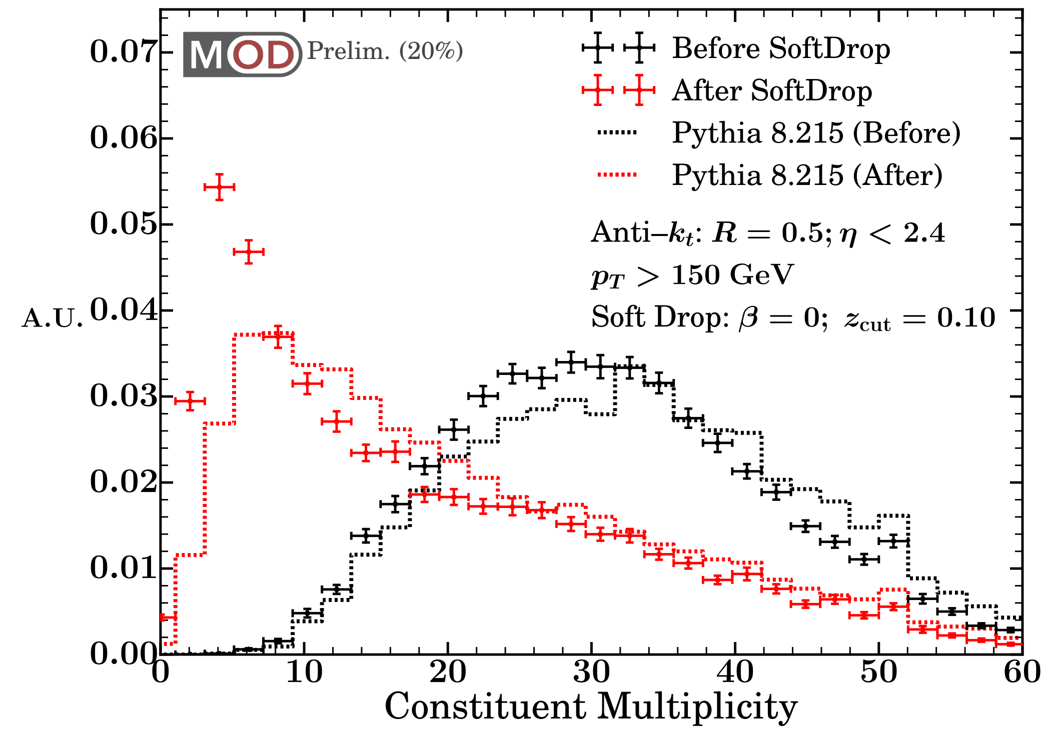


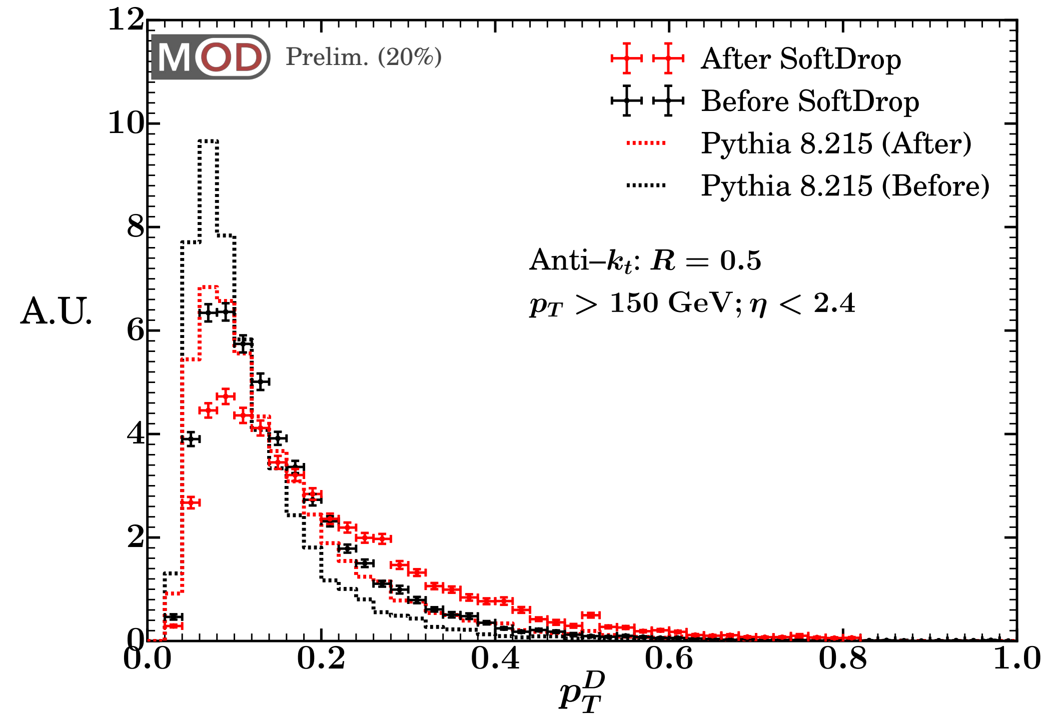
Jet Kinematics



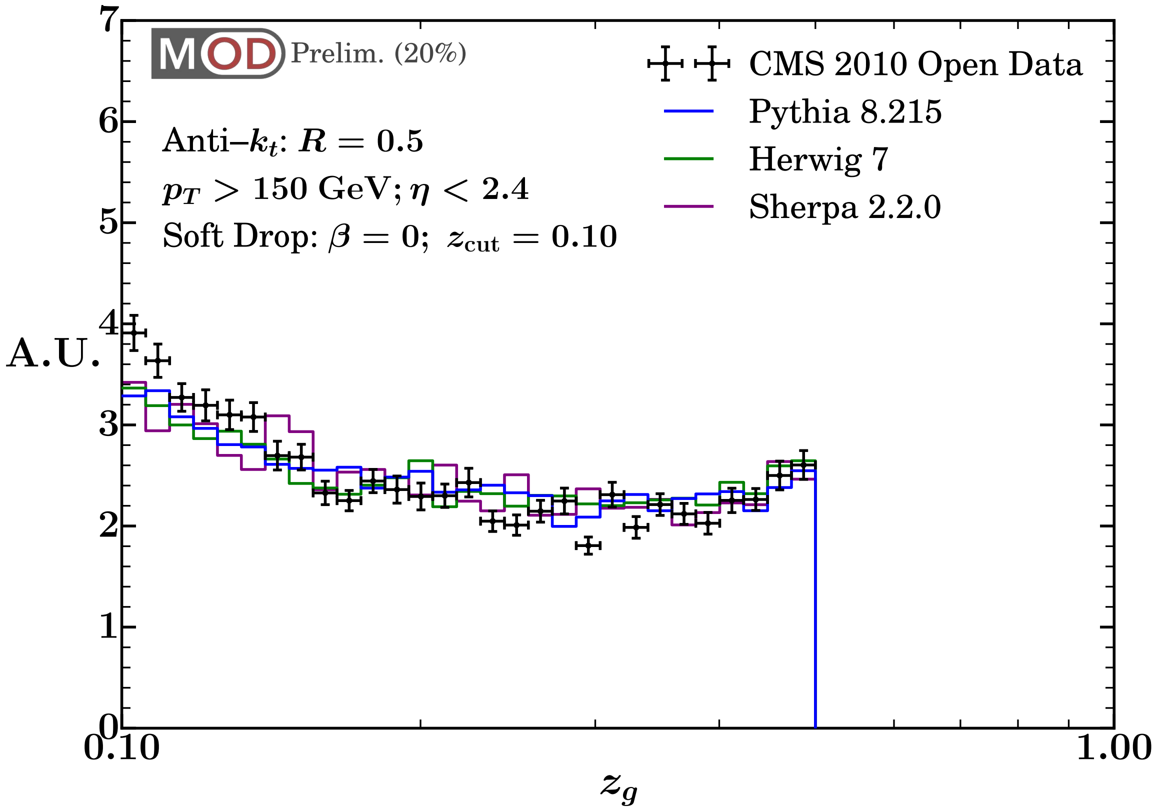
Simple Substructure

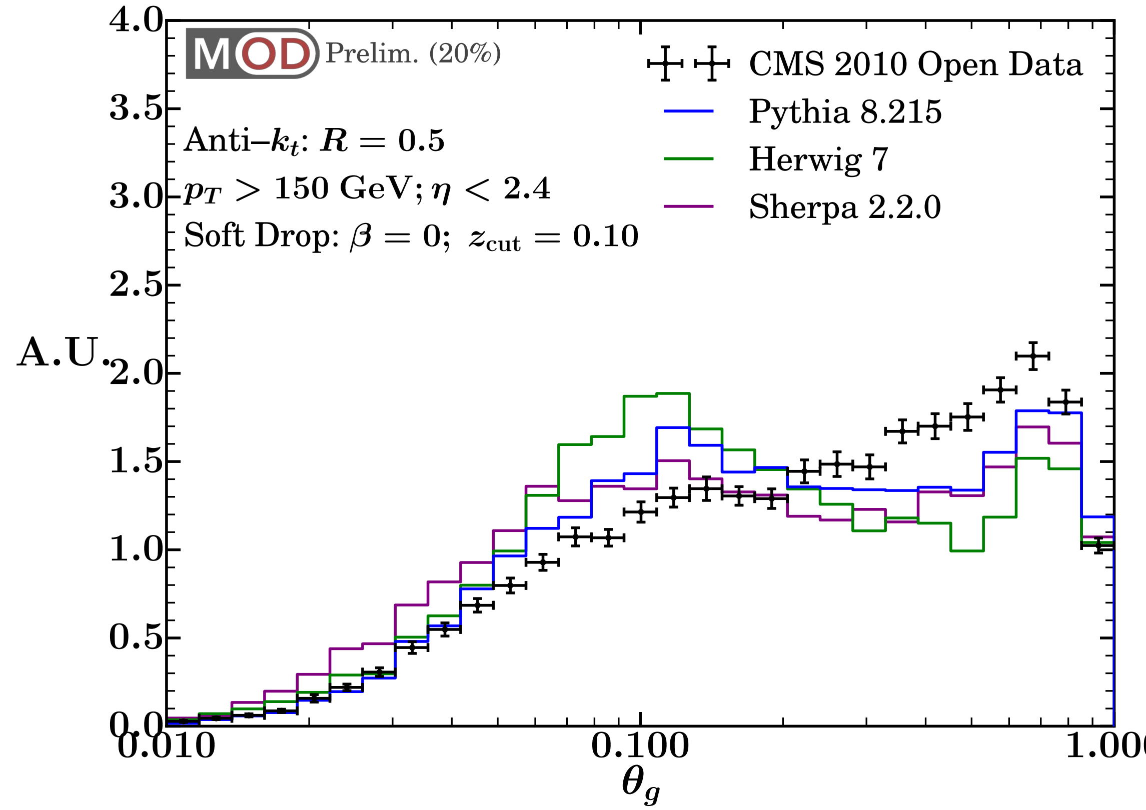


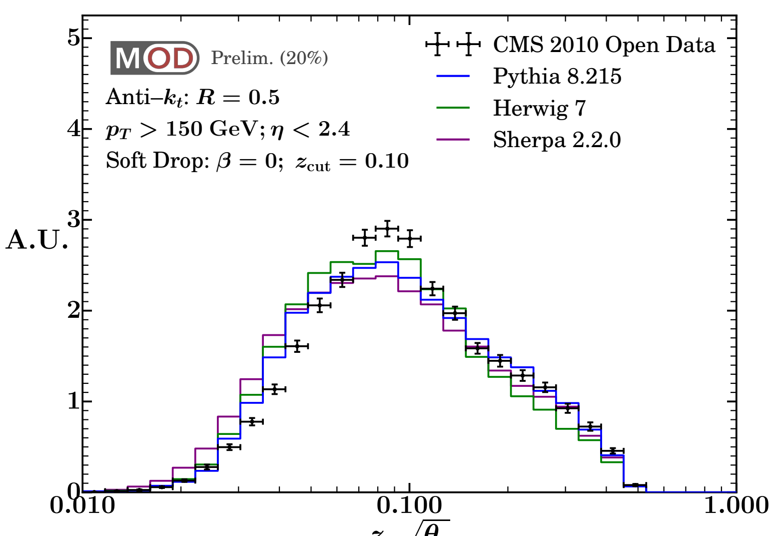


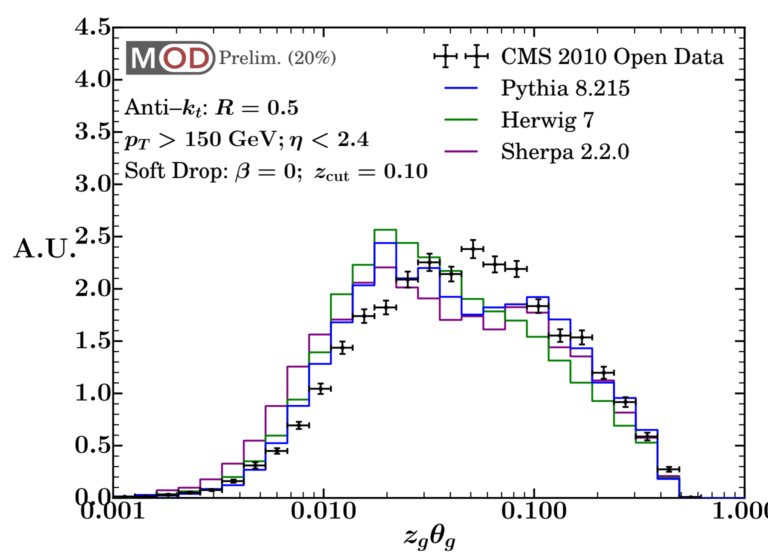


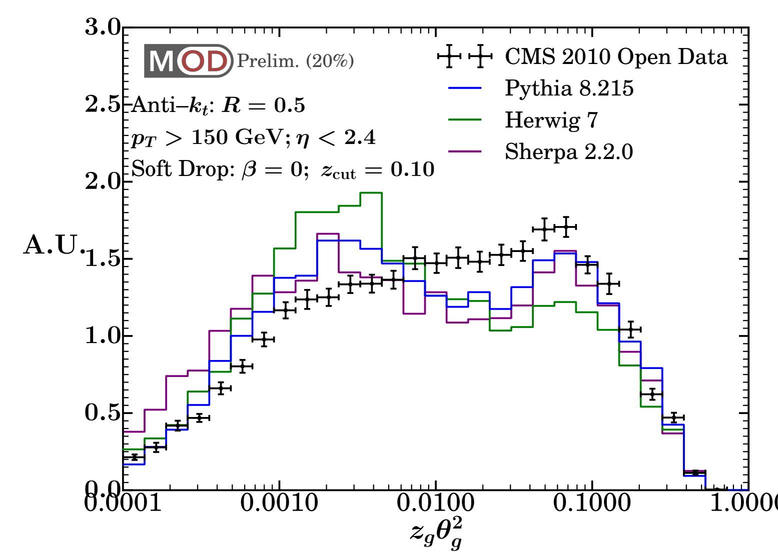
2-prong Substructure



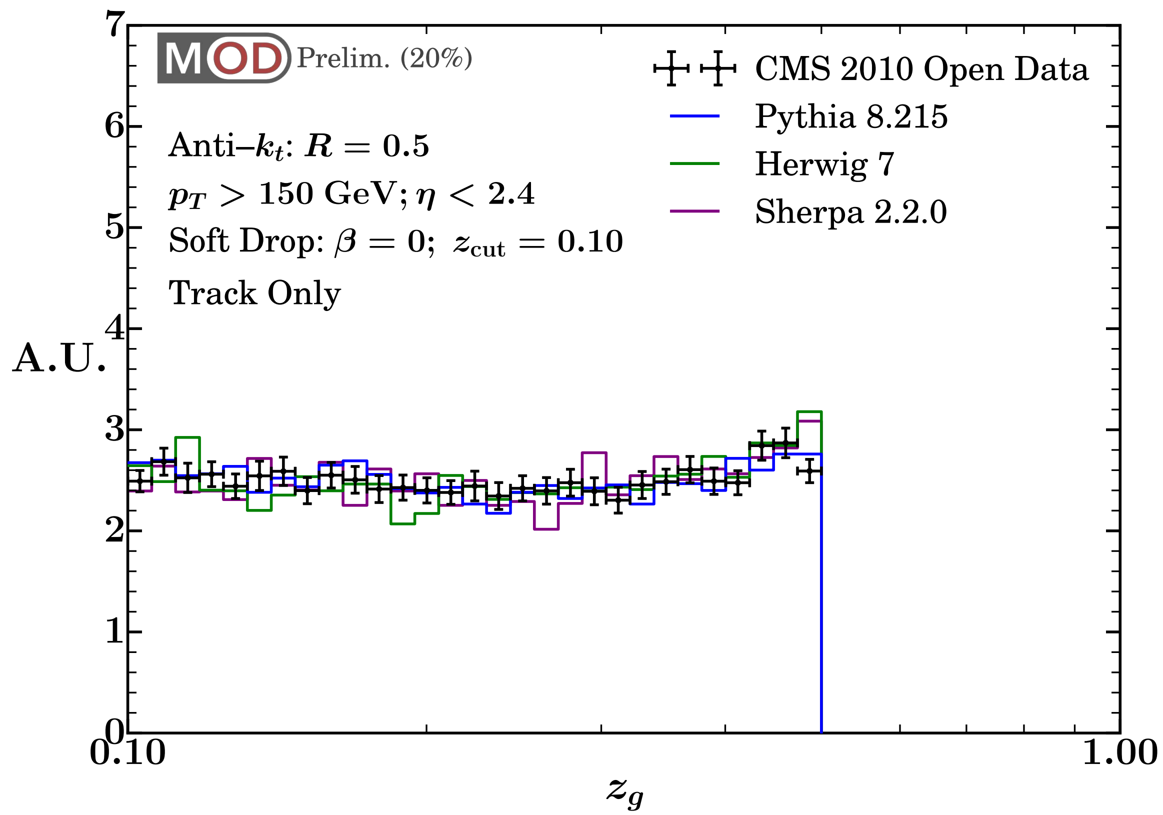


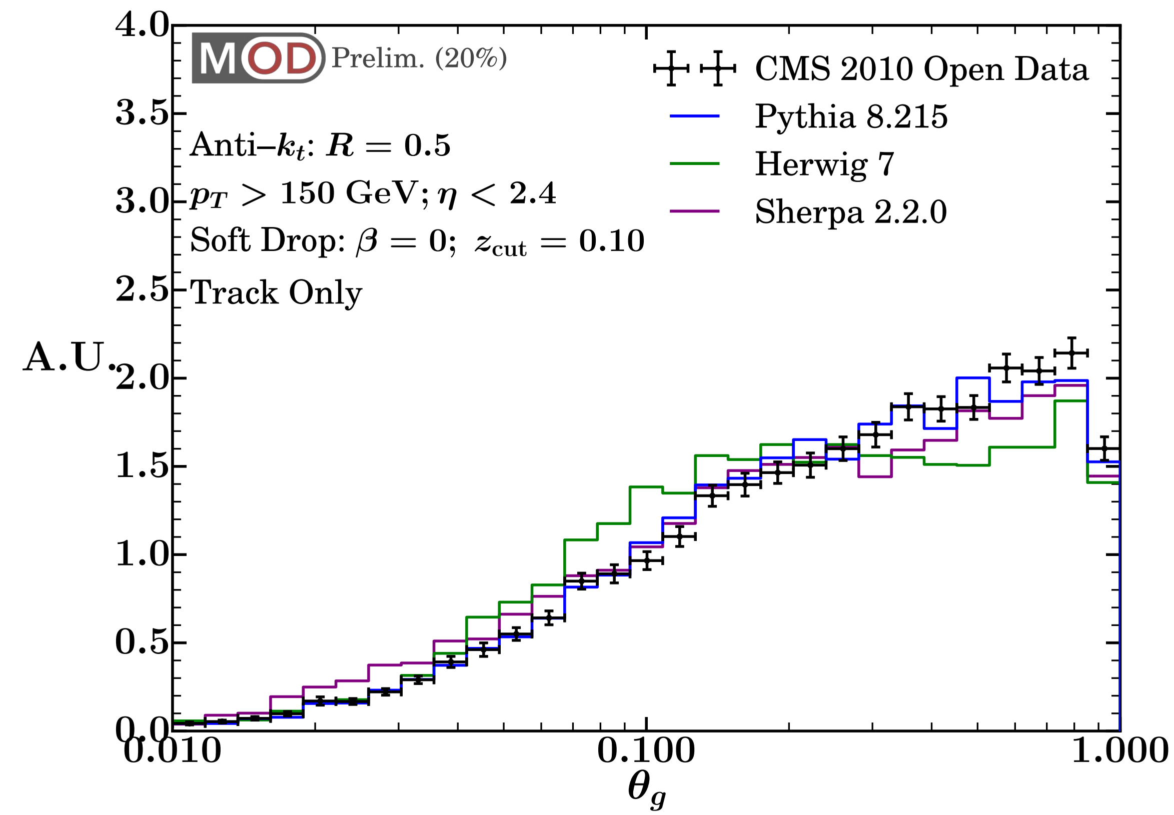


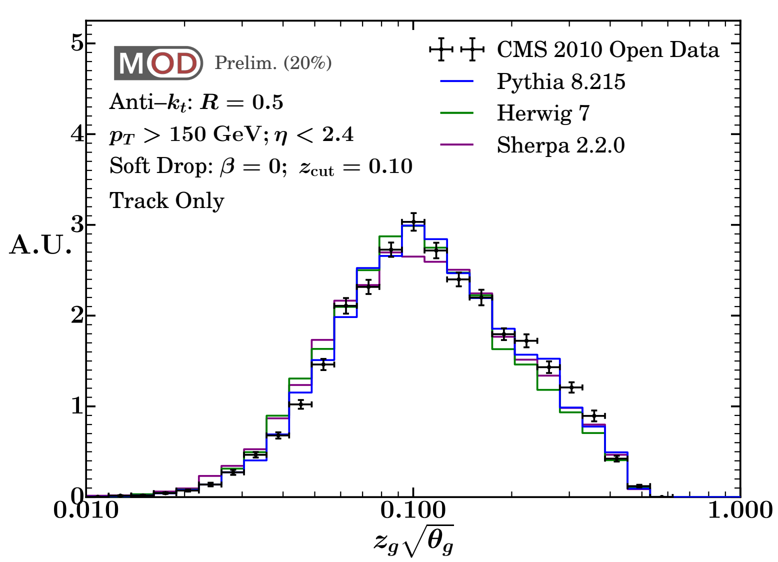


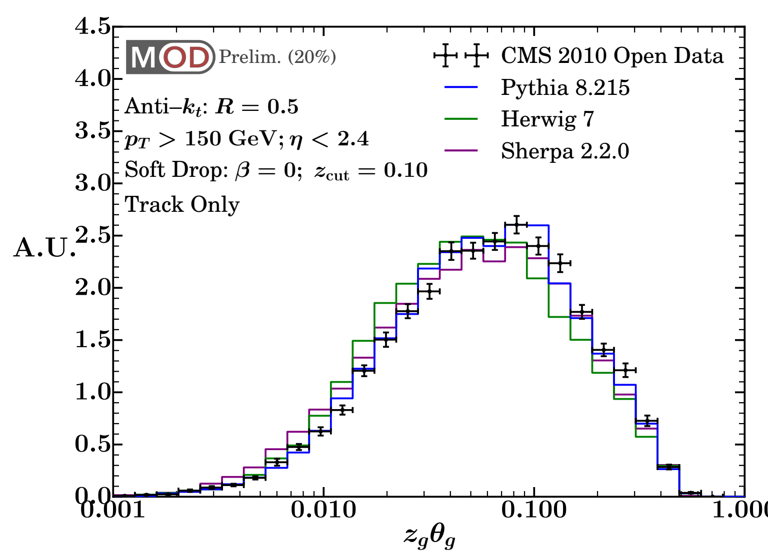


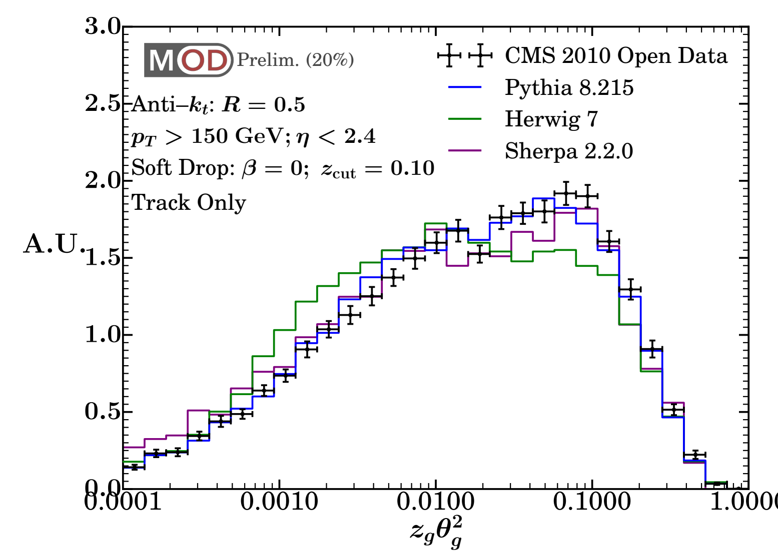
Track-Only Substructure











Changing z_{cut}